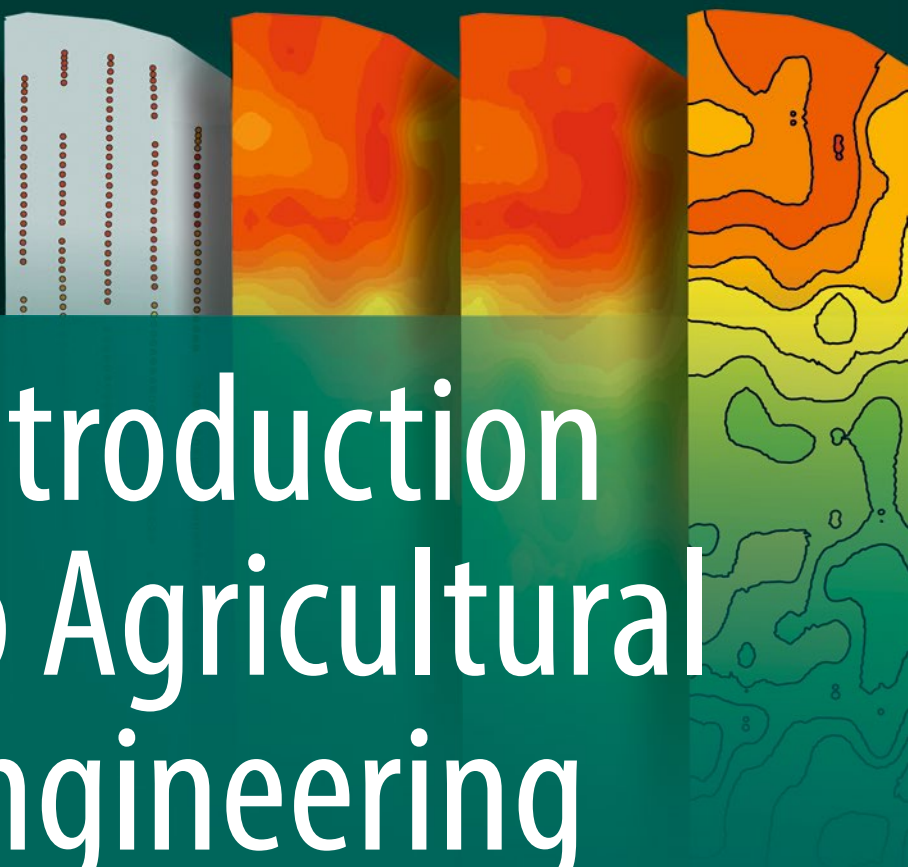
Harry L. Field · John M. Long



Introduction to Agricultural Engineering Technology

A Problem Solving Approach

Fourth Edition

Springer

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Harry L. Field • John M. Long

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Preface

This text is intended for any class or reader interested in improving their knowledge about agriculture and enhancing their abilities in solving problems common to agriculture. It is an update of *An Introduction to Agricultural Engineering Technology* by Field and Solie. This edition includes a new chapter on site-specific crop management.

The topics and their treatment were selected for three reasons: (1) to acquaint individuals with a wide range of applications of engineering principles to agriculture, (2) to present a selection of independent but related topics, and (3) to develop and enhance the problem-solving ability of the individual.

Each chapter contains educational objectives, introductory material, and example problems (where appropriate). Most chapters are self-contained and can be used independently of the others. Those that are sequential are organized in a logical order to ensure that the knowledge and skills needed are presented in a previous chapter.

As principal author, I wish to express my gratitude to Dr. John Long for his technical assistance, for writing the chapter on site-specific crop management, and for reviewing the text.

Stillwater, OK, USA Harry L. Field

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Chapter 1
Problem-Solving

1.1 Objectives

1. Be able to define problem-solving.
2. Be able to describe the common problem-solving methods.
3. Be able to select the appropriate method for solving a problem.
4. Understand the function and use of spreadsheets.
5. Understand the use of and common symbols for flow charts.

1.2 Introduction

Problem-solving is a part of living. We face many problems on a daily basis. Some of these problems occur because of the environment, others involve people and human relations, and some require the use of math. In this chapter, we will discuss problems involving mathematical solutions and several ways these problems can be approached.

1.3 Mathematical Problem-Solving

Mathematical problem-solving is the process by which an individual uses previously acquired knowledge, skills, and understanding to satisfy the demands of an unfamiliar situation. The essence of the process is the ability to use information and facts to arrive at a solution. Remember two characteristics when solving problems using mathematical processes:

1. Mathematical processes do not always provide the answer. They may just provide more information that can be used to make a more informed decision. Good decision-making requires good information.
2. Establish levels or intervals of acceptability whenever perfection is not possible or expected. When perfection is not possible, the amount of error that is acceptable must be determined. Several resources are available for determining

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the acceptable level of error. These include experts, standards, manufacturers' recommendations, comparison to other situations or machines, personal experiences, and others.

Both of these characteristics will be explained using examples and sample problems in later chapters.

One of the objectives of this chapter is to increase the reader's knowledge of problem-solving methods. The following sections discuss seven different approaches to solving mathematical problems. These are diagrams and sketches, patterns, equations and formulas, unit cancellation, intuitive reasoning, spreadsheets, and flow charts.

1.3.1 Diagrams and Sketches

Some problems involve the determination of a quantity of items, such as the number of nails per sheet of plywood or the number of studs in a wall. In solving these types of problems, it usually is helpful to draw a sketch or a diagram.

Problem How many posts are needed to build a fence 100 feet long with posts 10 feet apart?

Solution For many people, the first response would be 10:

$$\text{Posts} = \frac{100 \text{ ft}}{10.0 \text{ ft/Post}} = 10 \text{ posts}$$

but a diagram, Fig. 1.1, shows that the correct number of posts is 11.

This is an example of a situation where a wrong answer is possible if you do not interpret the problem correctly. In this example, 10 is not the number of posts. It is the number of spaces.

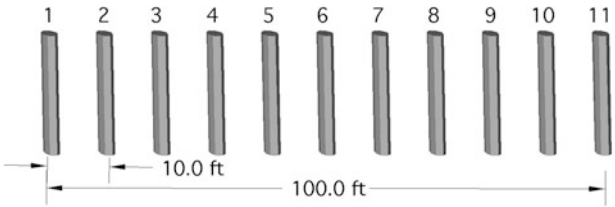

Fig. 1.1 Number of posts

1.3.2 Patterns

The solution to some problems may depend upon one's ability to discover a pattern in an array of numbers or values. Frequently, it is convenient to examine the patterns in a sample rather than the entire population. Once a pattern is discovered and shown to be consistent for the sample, it can be used to predict the solution for the entire population.

Table 1.1 Patterns in numbers, first sample

		Cow number									
Ration	Child	1	2	3	4	5	6	7	8	9	10
Grain	1	N	N	N	N	N	N	N	N	N	N
Mineral	2		Y		Y		Y		Y		Y
Hay	3			Y			Y			Y	
Silage	4				Y				Y		
Water	5					Y					Y

Problem A dairy farmer has five children. Each child is responsible for one part of the daily feed ration for the family's 100 dairy cows. The oldest is responsible for the grain, the second for the minerals, the third for the hay, the fourth for the silage, and the fifth for the water. Instead of feeding each cow, the first child decides she will not feed the cows at all that day. The second child decides just to feed every other cow, the third child feeds every third cow, and so on. Dad soon discovers how the cows were fed and needs to know which cows did not receive any feed or water.

Solution When one is faced with this type of problem, it is usually helpful to set up a table. In this case, it would be very time-consuming to set up a table for all 100 cows. Instead, select a sample of the cows. If a pattern is true for the sample, there is a high probability that the pattern will be true for a large group. Determining the size of a sample is not always easy. Pick one, and if a clear pattern does not appear, increase the size until a pattern develops. We will start with the first ten cows (Table 1.1).

In this sample, cows #1 and #7 did not receive any grain, mineral, hay, silage, or water. Is this enough information to establish a pattern? We will predict that the next cow that did not receive any feed or water is #11. Why? To test this prediction, the sample size must be extended to include a larger number of cows.

Table 1.2 shows that the prediction was right; cow #11, along with #13, #17, and #19, did not receive any grain, minerals, hay, silage, or water. It is now safe to consider that the prediction could be used to identify all of the animals within the herd that did not receive any grain, minerals, hay, silage, or water (those animals represented by prime numbers, i.e., a number divisible only by itself and one).

Table 1.2 Patterns in numbers, second sample

		Cow number									
Ration	Child	11	12	13	14	15	16	17	18	19	20
Grain	1	N	N	N	N	N	N	N	N	N	N
Mineral	2		Y		Y		Y		Y		Y
Hay	3		Y			Y			Y		
Silage	4		Y				Y				Y
Water	5					Y					Y

1.3.3 Equations and Formulas

Equations and formulas are similar but different. All formulas are equations, but not all equations are formulas. Many sources consider the terms interchangeable. The following sections will explain the difference.

1.3.3.1 Equations

An equation is a statement that declares two quantities as being equal by using an equal (=) sign. Equations are useful because they show the equality relationship between the variables in a problem, such as $a = 2b$. Determining the value for the variables to make the equation true solves the equation. The example uses a simple equation with only two variables; consequently, there are more than one set of numbers that will make the equation true, $a = 4$ & $b = 2$, $a = 8$ & $b = 4$, etc. All combinations have the same relationship: b is one half of a. This may be an appropriate answer, but other equations will have only one set of numbers that will make both quantities equal. Equations can be developed, modified, or adapted to solve any problem.

Problem Determine, using an equation, the length of fence wire required to build a single wire fence around a rectangular field measuring 450 feet on the long side and 350 feet on the short side.

Solution The fence forms a perimeter around the rectangular field. The solution of the problem is an equation that will solve for the perimeter of a rectangular field. The unknown quantity is the perimeter, and the known quantities are the length and width. Begin by assigning the variables L to represent the length, W to represent the width, and Pr to represent the perimeter. A rectangle has four sides, two long sides and two short sides. The equation for finding the perimeter is:

$$\mathrm{Pr} = (L_1 + L_2) + (S_1 + S_2)$$

substituting the known values:

$$\begin{aligned}\mathrm{Pr} &= (450\ \mathrm{ft} + 450\ \mathrm{ft}) + (350\ \mathrm{ft} + 350\ \mathrm{ft}) \\ &= 900\ \mathrm{ft} + 700\ \mathrm{ft} \\ &= 1600\ \mathrm{ft}\end{aligned}$$

The field will require 1600 feet of wire. This equation can be used to determine the length of wire for any rectangular field.

Being a rectangular field, the equation can also be written as $\mathrm{Pr} = 2L + 2S$. The first equation could be modified to solve for the length of wire that would be needed for a four-sided field that is not a rectangle, but the second one could not.

Problem Determine, using an equation, the amount of fence wire required to build a single wire fence around a four-sided field with two long sides of 450 feet and two short sides of 350 feet and 225 feet.

Solution Substituting the values:

$$\begin{aligned}\text{Pr} &= (L_1 + L_2) + (S_1 + S_2)\\ \text{Pr} &= (450\text{ ft} + 450\text{ ft}) + (350\text{ ft} + 225\text{ ft})\\ &= 900\text{ ft} + 575\text{ ft}\\ &= 1475\text{ ft}\end{aligned}$$

To solve this problem with the second equation, it must be modified.

$$\begin{aligned}\text{Pr} &= 2L + (S_1 + S_2)\\ \text{Pr} &= (2 \times 450\text{ ft}) + (350\text{ ft} + 225\text{ ft})\\ &= 900 + 575\\ &= 1475\text{ ft}\end{aligned}$$

This example illustrates that the ability to develop and adapt equations is a required skill when using equations.

1.3.3.2 Formula

A formula is a group of mathematical symbols, representing variables, which express a specific relationship. Formulas can be treated as a recipe or set of instructions that will produce a specific result. An example is the formula used to solve for the area of a circle, $A = \pi r^2$. The same variables, A and r, are used each time, and the relationship of the variables is the same each time the area of a circle is calculated. Many formulas also contain a constant. The formula for the area of a circle also illustrates this principle. The variable pi (π) is a constant.

There are at least two important considerations when using formulas.

1. You must substitute values with the correct units of measure for each variable. All formulas have specific units of measure for each variable. If the units are incorrect, the answer will be incorrect. The formula used to determine the application rate of a boom-type sprayer is an example.

$$\text{Application rate}\,\frac{\text{gal}}{\text{ac}} = \frac{5940 \times \text{Flow rate (gal/min)}}{\text{Speed (min/hr)} \times \text{nozzle spacing (in)}}$$

If the constant, 5940, is not included, the units in the answer will evaluate to: $\frac{\text{gal}}{\text{min}} \times \frac{\text{hr}}{\text{min}} \times \frac{1}{\text{in}} \neq \frac{\text{gal}}{\text{ac}}$ which is not correct.

Unit conversion values must be used for the formula to produce the correct answer. These unit conversion values are used each time the application rate is calculated. This formula is an example of a situation in which the unit conversion values that are always used each time the problem is solved are combined into a constant, 5940. When the application rate is determined using an equation that includes all of the unit conversion values, the source of the constant becomes apparent:

$$\frac{\text{gal}}{\text{ac}} = \left[\frac{\text{gal}}{\text{min}} \times \frac{\text{hr}}{\text{mi}} \times \frac{1}{\text{in}}\right] \times \frac{60\text{ min}}{1\text{ hr}} \times \frac{1\text{ mi}}{5280\text{ ft}} \times \frac{12\text{ in}}{1\text{ ft}} \times \frac{43{,}560\text{ ft}^2}{1\text{ ac}}$$

$$= \frac{\text{gal}}{\text{ac}} \times \frac{31{,}363{,}200}{5280}$$

$$= \left[\frac{\text{gal}}{\text{ac}}\right] \times 5940$$

Notice that the three-bracketed variables of the formula, flow rate, velocity, and nozzle spacing, are included in the application rate equation.

It is important to remember that when using a formula, the variables must be entered with the correct unit of measure. If the unit of measure for the variable is not correct, it must be converted, or an additional unit conversion variable must be added. This will change the constant that must be used.

2. Many formulas contain equal signs and thus can be treated as equations. A situation may arise where the result of a formula is known but an input variable may be the unknown. This requires the ability to rearrange the formula to solve for the unknown value. The application rate formula has four variables: application rate, flow rate, velocity, and nozzle spacing. It is possible that you know the desired application rate but need to determine the nozzle spacing. This requires that we treat the application rate formula as an equation. Rearranging and solving for nozzle spacing in inches (nsi):

$$\text{Nozzle spacing (nsi)} = \frac{5940 \times \text{Flow rate (gal/min)}}{\text{Speed (mi/hr)} \times \text{Application rate (gal/ac)}}$$

Through this rearrangement, a new formula for nozzle spacing has been produced. Most formulas are equations because they show the equality of two quantities, but not all equations are formulas because equations do not always represent a specific relationship. This difference is a small mathematical nuance; therefore, for the remainder of this text, the terms equation and formula are used interchangeably.

1.3.4 Unit Cancellation

Patterns, equations, and formulas solve many problems, but they require a more than minimum level of algebra skills. A less intense algebraic method for solving mathematical problems in agriculture is called the unit cancellation method. The unit cancellation method, or unit method, develops the equation needed to solve the problem by ensuring the unwanted measurement units are eliminated and only the desired unit of measure for the answer remain. Variables without units such as π can also be included. The unit cancellation method follows two mathematical principles:

1. The unit of measure associated with the number (feet, gallons, minutes, etc.) follows the same mathematical rules as the number.
2. The measurement unit of the number behaves according to the rules of fractions.

For example:

$$2 \times 2 = 4 \text{ or } 2^2$$

With units of feet the same equation is:

$$2 \text{ ft} \times 2 \text{ ft} = 2 \times 2 \text{ and ft} \times \text{ft or } 4 \text{ ft}^2$$

To review the rules of fractions, study the following example:

$$\frac{3}{4} \times \frac{4}{5} = \frac{3 \times 4}{4 \times 5} = \frac{3}{5}$$

In this example, the 4's in the numerator and denominator cancel out (4/4 = 1).

When the units of measure are included, they behave in the same way:

$$\frac{3 \text{ ton}}{4 \text{ hour}} \times \frac{4 \text{ hour}}{5 \text{ day}} = \frac{12 \text{ ton}}{20 \text{ day}} = 0.6 \frac{\text{ton}}{\text{day}}$$

In this example, the 4's and the units associated with them cancel out. The un-canceled units become the units for the answer. The following example shows another variation of this principle (where gal = gallon and hr = hour):

$$5 \frac{\text{gal}}{\text{hr}} \times 3 \text{ hr} = 15 \text{ gal}$$

In this example, the unit of hour in the numerator and denominator cancel each other, leaving the unit of the answer in gallons.

Problem What is the weight (lb) of one pint of water?

Solution If a scale and a one pint measure were available, it would be a simple task to weigh the pint of water. An alternative is to use the conversion factors found in a table of weights and measures (Appendix I) and the unit cancellation method.

Note, in this example, two types of measure are used: volume and weight. The heart of the problem is to find the conversion value(s) that will convert from volume (pints) to weight (pounds). This value is the density of water.

To begin, refer to Appendix I and identify conversion factors that use both volume and weight. You should find that 1 cubic foot contains 7.48 gallons and 1 gallon contains 8 pints. This is a start, but you need something more. If you also know that water weighs 62.4 pounds per cubic foot, the problem is solved with (lb = pounds, gal = gallons, pt = pints, and ft^3 = cubic feet):

$$\begin{aligned} \frac{\text{lb}}{\text{pt}} &= \frac{62.4 \text{ lb}}{1 \text{ ft}^3} \times \frac{1 \text{ ft}^3}{7.48 \text{ gal}} \times \frac{1 \text{ gal}}{8 \text{ pt}} \\ &= 1.04 \frac{\text{lb}}{\text{pt}} \end{aligned}$$

The units of pint, gallon, and cubic feet all cancel each other leaving the answer in the desired units of pound per pint. This example illustrates the principles and sequence of steps when using the unit cancellation method.

- Begin by writing down the correct units for the answer.
- Write down the equal sign (=).
- Begin entering the values and their units. The first value entered should have one of the desired units of the answer in the correct position (numerator or denominator), even if it is a unit conversion value from Appendix I or another source. Starting with one of the units of measure in the correct position will eliminate the possibility of having the right half inverted.
- Enter a value that will cancel out the unwanted units, if any, in the first value entered.
- Continue to add variables with the appropriate units until the only units that remain are the units of the answer.
- If all of the units cancel except the desired answer, and the units are in the correct position, then the only possible mistake is a math error in calculating the final answer.
- Calculate the final numerator by multiplying all of the numerators together.
- Calculate the final denominator by multiplying all the denominators together.
- For a final answer in decimal format, divide the numerator by the denominator.

The process of unit cancellation is also useful for problems requiring the development of a new unit. For example, a very common quantity in agriculture is power. Power is measured in different units, depending on whether it is electrical or mechanical. Mechanical power is measured in units of foot-pounds per minute. The solution to a problem in which a 24 ounce weight is moved 15 feet in 5 s would look like this (oz = ounces, sec = seconds, lb = pounds, ft = feet):

$$\begin{aligned}\text{Power}\left(\frac{\text{ft} \bullet \text{lb}}{\text{min}}\right) &= \frac{15\ \text{ft}}{5\ \text{sec}} \times \frac{60\ \text{sec}}{1\ \text{min}} \times \frac{1\ \text{lb}}{16\ \text{oz}} \times \frac{24\ \text{oz}}{1} \\ &= \frac{21{,}600\ \text{ft} \bullet \text{lb}}{80\ \text{min}} \\ &= \frac{270\ \text{ft} \bullet \text{lb}}{\text{min}}\end{aligned}$$

(Note that lb. • ft. is a compound unit, not feet minus pounds or feet times pounds.) This same process will work just as well for problems with units that are more complex and have more variables.

1.3.5 Intuitive Reasoning

Intuitive reasoning is a process by which an individual arrives at a correct answer through insight or a hunch, usually without being able to explain the process used. The actual process depends on the individual and cannot be defined in progressive steps.

Problem You ask your employees to determine how many vehicles in the parking lot need their seat covers replaced. They return with an answer of 150. Then you realize you need to know how many single seat pickups and how many cars with

two seats. Your employees remember that there were the same number of cars in the lot needing seat covers as pickups; so how many car and how many pickup seat covers do you need?

Solution Some people would solve this problem algebraically, but with intuitive reasoning, a series of approximations can be developed. If there were 20 cars and 20 pickups, you would need 60 seat covers [$(20 \times 1) + (20 \times 2) = 60$], if 40 cars and 40 trucks 120 seat covers, and if 60 of each then 180 seat covers. The answer must be less than 60 and more than 40. The correct number of vehicles is 50. Which means you would need 50 pickup seat covers and 100 car seat covers.

1.3.6 Spreadsheets

The adoption of computers has provided a very useful problem-solving method. This is the spreadsheet.

A spreadsheet is a very powerful data management tool that provides a means to enter, manipulate, and plot data and also information. The features of spreadsheets programs are not all the same, but they all include several common features. Some of the common features and uses of spreadsheets are presented in the following sections.

1.3.6.1 Data Entry

Before a computer can manipulate data, it must be able to locate it. Spreadsheet programs accomplish this by using a grid or array consisting of columns and rows. A single grid is usually called a sheet or page. Most spreadsheet programs use letters to identify columns and numbers to identify the rows. The junction of each row and column is called a cell. The labels used for the columns and rows give each cell a unique address or location; see Fig. 1.2.

The location of the "X" in Fig. 1.2 is A1, and the cell that has the "XX" is cell E6. The number of columns and rows in a spreadsheet is limited by the memory of the computer or by the spreadsheet program. Spreadsheets can store and manipulate large amounts of information. A grid with 256 columns and

	A	B	C	D	E	F	G	H	I	J
1	X									
2										
3										
4										
5										
6					XX					
7										
8										
9										
10										

Fig. 1.2 Columns and rows of a spreadsheet

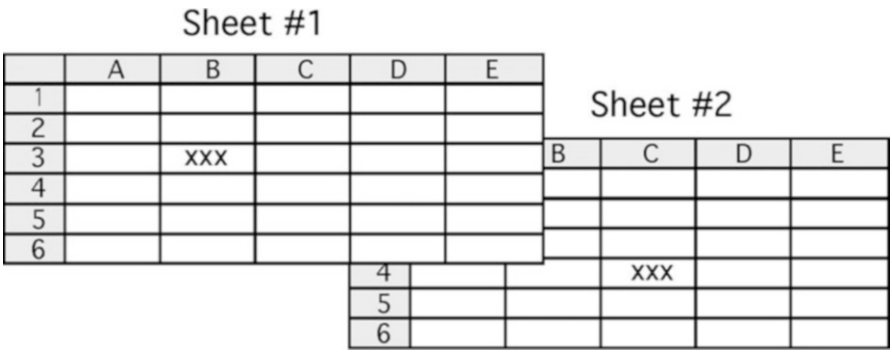

Fig. 1.3 Linking sheets in a workbook

10,000 rows has 2,560,000 individual cells for data or information. Cells in a spreadsheet can contain text or numbers, and both text and numbers can be manipulated. Text and numbers are typically entered into the spreadsheet via the keyboard. Spreadsheets also provide copy and paste functions and other ways to input data.

Spreadsheets contain features for manipulating data. One example is the ability to link information in different sheets or pages. For example, one type of spreadsheet uses the term "workbook" to describe a spreadsheet file. Each workbook can have several pages and the data in one page can be linked to another page. In this spreadsheet, if cell B3 in sheet #1 contained the equation "=Sheet2!C4," that cell would display the contents of cell C4 in sheet #2 (Fig. 1.3).

Although the primary purpose of spreadsheets is the manipulation of data, text can also be entered into cells to organize and label the data. Text can also be used to manipulate data.

When setting up a spreadsheet, the individual should spend some time studying the data to determine the best structure of the spreadsheet. Answering questions about the number of columns, the number of rows, what cells will contain subtotals, etc., and the location of the outputs before starting the data entry will prevent problems that force a restart or the reorganization of the data. This will also make the spreadsheet easier to use and reduce the number of mistakes that will occur.

Another reason for the popularity of spreadsheets is the ability to output the data in different formats. Spreadsheets can output data in charts, graphs, and text that can be displayed by the program or exported to presentation programs.

1.3.6.2 Data Manipulation

Data in spreadsheets can be manipulated with any mathematical operation. The user selects the cell for the answer and identifies the location of the data and inserts or writes the equation for the desired computation. The data can be in single cells, a

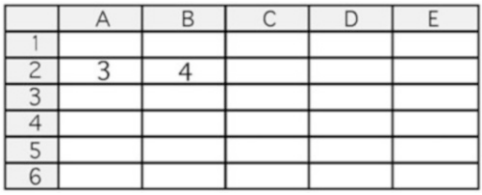

Fig. 1.4 Adding data in spreadsheet

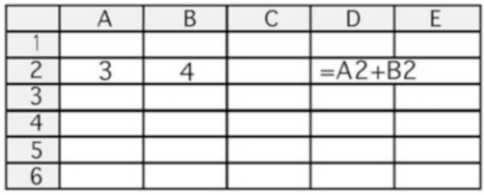

Fig. 1.5 Example of mathematical operation in a spreadsheet

row of cells, a column of cells, or a grid of cells. The spreadsheet program and the user's ability to use it are the only limits to the complexity of equations that can be used.

For example, if the desired operation in Fig. 1.4 is finding the sum of two numbers and have the answer appear in cell D2, the user selects cell D2 and enters the equation = A2 + B2 (Fig. 1.5).

Note the equation starts with the "=" sign. In most spreadsheets, starting with the "=" sign tells the computer that a mathematical process will be performed on data from other cell(s) and the results displayed in the cell with the equal sign. This is a simple example, but all mathematical operations are entered in the same way.

Functions

To expedite the data manipulation process, spreadsheets also include functions. A function performs a specific operation on the input data to produce a specific output. Functions can be as simple as sum and average or as complex as square root, trigonometric functions, and many other more complex math operations. Functions are usually accessed through a menu system. Functions may be organized into categories. Not all functions will be explained in this text. Two examples will be included to show how functions are entered into a spreadsheet and how they work. The previous addition example in Fig. 1.5 can be completed using the sum function (Fig. 1.6).

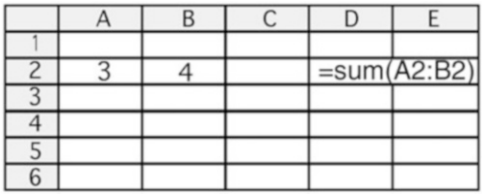

Fig. 1.6 Addition using the sum function

	A	B	C	D	E	F	G	H	I	J
1										
2	2	4	8	21	45	234		=sum(A2:F2)		
3		5								
4		8								
5		10								
6		234								
7		782								
8										
9		=sum(B2:B7)								
10										

Fig. 1.7 Using sum function with multiple numbers

In this example, 7, the sum of 3 and 4, would appear in cell D2. The advantage of the sum function is much more apparent when larger data sets are used (Fig. 1.7).

Figure 1.7 also illustrates that cells can be summed both horizontally and vertically. The sum function will also be used to add up a grid of cells. Using the sum function is much simpler than writing the equation when adding several numbers. To write the equation using the "+" operator, each cell reference must be included with a "+" in between. The equation "= A2 + B2 + C2 + D2 + E2 + F2" would be entered into cell H2 to sum all the numbers in row #2. The "sum" function is used by entering an = into the cell where the answer is desired and then typing sum. Next enter the left parenthesis "(." The third step is entering the beginning and ending cell references separated by a ":". Finish by entering the right parenthesis ")" into cell H2 and hit the enter/return key (Fig. 1.7). When the same function will be used for several rows or columns of data, the appropriate fixed or relational reference must be used. This is explained in a following section.

It cannot be demonstrated in this text, but inserting functions is easier than the previous description because the cells can be entered by highlighting the desired cells instead of typing the beginning and ending cell references. All of the functions are entered in a similar manner. In the second example, a logic function will be used to make a decision about the data.

Logic Functions

Another feature of spreadsheets is logic functions. Logic functions are expressions such as "IF," "AND," "FALSE," "NOT," "OR," and "TRUE." A logic function is an equation that adds decision-making capabilities. Logic functions are very useful because they are used to compare the values of cells, draw a conclusion based on the data in the cells, and express the conclusion in a cell. The "IF" logic function compares the values in a set of cells and returns a number or word based on the logic statement. For example, a flour miller must constantly monitor the percent of flour milled from the wheat because a drop in the flour yield rate indicates a problem

	A	B	C	D	E	F	G	H
1			Date					
2		10/10/04	10/11/04	10/12/04	10/13/04	10/14/04	10/15/04	10/16/04
3	Pounds wheat	10562	11584	11698	10962	11532	11846	10624
4	Pounds flour	8215	10634	10692	10854	10237	10687	9634
5	% Yield	77.78	91.80	91.40	99.01	88.77	90.22	90.68
6		Error				Error		
7								

Fig. 1.8 Spreadsheet using the "IF" function

during the milling process. The "IF" function can be used to trigger an error or warning message when the yield drops below the desired rate (Fig. 1.8).

In this example, the "IF" function was used to trigger the spreadsheet to insert the word "error" whenever the percent yield of flour was less than 90% and to leave the cell blank when the flour yield was 90% or more. The function used in B6 through H6 is written as =IF(reference cell < 90,"Error"," "). For cell B6 the equation is written as =IF(B5<90,"Error"," "). The function says if the value in B5 is less than 90, enter Error in cell B6, and if the value in B5 is 90 or greater, then leave cell B6 blank. The user has three ways to enter the function into cells B6 through H6.

The function could be typed into each one of the cells. When this option is used, the function must be modified for each cell because the cell location for the percent yield that is used in the function changes columns. For example, when entering the function into cell C6, the correct function is =IF(C5 < 90,"Error"," ").

The function could be typed into cell B6, copied, and then pasted into each cell from B6 to H6. When this method is used, relational cell reference must be used. This is explained in the next section.

The easiest way to enter the function into the adjoining cells is to use the fill option. When using the fill option in the example, the function was typed into cell B6 and filled into the adjoining cells. The fill function also requires relational cell reference. The keystrokes required to complete the fill option are not explained in this text because they are not consistent across the different spreadsheet program versions. The key strokes for the fill option is one that users should memorize because it is very useful for entering equations and functions in the cells of spreadsheets.

Spreadsheets are very powerful tools and allow a lot of flexibility in how they are set up. Through study and practice, they can be used for very complex calculations and logic statements.

Relational or Fixed Reference

The terms relational or fixed reference describe how a function treats the input data cells when the function is copied or filled into other cells. If the input data cell is set to fixed reference when the function is copied or filled, the exact function or equation is copied or filled into other cells. If the reference for cell B5 in Fig. 1.8

was fixed before the function in B6 was copied or filled into cell C6, the function in cell C6 would be = IF(B5 < 90,"Error"," "). This would be an error because cell C6 would display the logic statement for B5 instead of C5. When the desire is for the input data cell to change when the function moves to a different cell, relational reference should be used.

In the previous example, Fig. 1.8, the reference cell "B5" was not fixed because the desired outcome was to use the same function to evaluate the data in row 5 for columns C through H to determine if the data in row 5 met the 90% standard. This is an example of using a relational reference. When the function in B6 was copied to the adjoining cells, C6 through H6, the reference cells changed to the appropriate ones for that column. The next section will demonstrate the use of fixed data cells.

When data or reference cells are fixed, the data input cell or cells used by the function do not change when the function is copied or filled into additional cells. For example, the miller in the flour example could design the spreadsheet so the trigger point for the yield error message could be changed without retyping all of the equations. This is accomplished by adding a cell and having it contain the desired trigger point for the error message (Fig. 1.9).

Compare Figs. 1.8 and 1.9. In Fig. 1.9, the input data for the error statement has been added to B1, and the data has been shifted down one row. Cell B1 was changed to fixed reference before the function in B7 was copied or filled. Changing the value in B1 will also change the number used in B7 through H7 to trigger the error statement. This is accomplished by changing the logic statement in the function from a number, 90, to cell B1. When the function in B7 is copied from B7 through H7, the cell that the function checks for the logic question does not change. The function in cell B7 reads =IF(B6 < B1,"Error"," "). The spreadsheet used to develop these examples fixes the reference by placing a "$" in front of the column and row label. The spreadsheet also allows the column, the row, or both to be fixed. Inserting a $ in front of the column designator will fix the column reference when the cell is copied or filled, but the row designator will stay relational. The same is true of the column designator if only the row designator is fixed.

These examples are just a hint at the type of data manipulation that can be accomplished using spreadsheets. Data manipulation is only limited by the amount of time available to write the equations or functions and the ingenuity of the user.

	A	B	C	D	E	F	G	H
1	Desired Yield	85	%					
2				Date				
3		10/10/04	10/11/04	10/12/04	10/13/04	10/14/04	10/15/04	10/16/04
4	Pounds Wheat	10562	11584	11698	10962	11532	11846	10624
5	Pounds Flour	8215	10634	10692	10854	10237	10687	9634
6	% Yeld	77.78	91.80	91.40	99.01	88.77	90.22	90.68
7		Error						
8								

Fig. 1.9 Spreadsheet using a fixed reference cell

1.3.6.3 Graphing/Charting

The terms graphing and charting refer to the conversion of spreadsheet data to graphs or charts. The process and keystrokes to produce a graph or chart from spreadsheet data are very similar; therefore, the terms will be used interchangeably in this discussion. Most people are visual learners. Viewing a chart will transfer information faster and easier than studying the same data in a table. The charting function of spreadsheets may not be as powerful as a dedicated graphing or presentation program. They will provide enough options and produce visuals that will satisfy the needs of the average user.

Producing a graph with a spreadsheet program has the same requirements as drawing one by hand. The computer must know what data should be plotted along the "X," "Y," and "Z" axes, if three-dimensional charts are used. The chart function should provide an opportunity to enter labels for each axis, the chart title, and data legends and values if desired. To demonstrate the charting function, a common land surveying problem will be used. One common type of survey is called a profile. A profile survey collects the required data for defining the topography of the earth's surface along a route. Common uses of this data include a utility line, sidewalk, road, or retaining wall. In this example, an underground drainpipe will be used.

A profile data table will provide the elevation for stations along the route of the survey. Profile survey data is easily managed in a spreadsheet. For more information on profile surveys, consult Chap. 15. Table 1.3 contains the data for a profile survey.

The numbers in the STA column is the station distance from the starting point, and the numbers in the ELEV column are the elevations along the profile.

The purpose of the survey is to determine if a drain outlet can be located 2.0 feet below the elevation of station "0.0." The drain will have a 1% slope. Table 1.4

Table 1.3 Profile data

STA	BS	HI	FS	IFS	ELEV
BM	3.56	103.56			100
0		103.56		4.89	98.67
27.3		103.56		4.67	98.89
35.6		103.56		5.1	98.46
41.2		103.56		5.89	97.67
56.9		103.56		4.68	98.88
63.4		103.56		3.61	99.95
75.9		103.56		4.01	99.55
80.7		103.56		4.65	98.91
93.5	4.04	103.92	3.68		98.88
BM			3.91		100.01
Sum	7.6		7.59		
Difference		0.01			
	AE=	0.02		0.01 < 0.02	

Table 1.4 Data table for profile plot

	A	B	C
1	Starting	96.67 ft	
2	Elevation		
3	Slope	1.0 %	
4			
5	Station	Profile	Drain elev.
6	0.00	98.67	96.67
7	27.3	98.89	96.94
8	35.6	98.46	97.03
9	41.2	97.67	97.08
10	56.9	98.88	97.24
11	63.4	99.95	97.30
12	75.9	99.55	97.43
13	80.7	98.91	97.48
14	93.5	99.88	97.61a

shows another sheet in the spreadsheet. The stations and their elevations have been transferred to sheet 2. Equations have been inserted into column C that calculates the elevation of the drain for that station. This is accomplished by pointing cell C6 to the desired starting elevation, B2, and inserting the equation =C6 + (A7*$B $3/100) into C7. The equation is filled through C14. Notice that in the equation, the reference for the starting elevation and the percent slope are fixed references.

A person with experience in design and construction would be able to study the data table and answer important questions about this drain, such as "What is the maximum depth of the drain?" or "What is the minimum depth of the drain?" and numerous others. The importance of these questions and their answers is easier to see if the data are plotted in a chart. The plot of the profile with the drain is shown in Fig. 1.10.

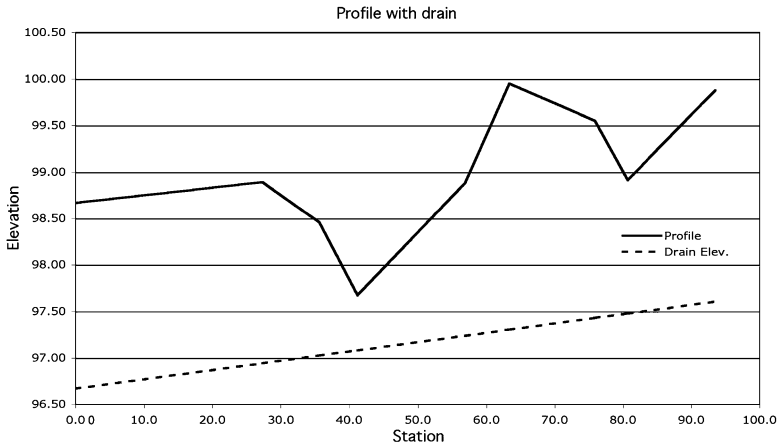

Fig. 1.10 Drain plot

Table 1.5 Drain table with 0.5% slope

	A	B	C
1	Starting		
2	Elevation	96.67 ft.	
3	Slope	0.5 %	
4			
5	Station	Profile	Drain elev.
6	0.00	98.67	96.67
7	27.3	98.89	96.81
8	35.6	98.46	96.85
9	41.2	97.67	96.88
10	56.9	98.88	96.95
11	63.4	99.95	96.99
12	75.9	99.55	97.05
13	80.7	98.91	97.07
14	93.5	99.88	97.14

Figure 1.10 shows the maximum depth of the drain occurs at station 63.4 and the difference between the surface elevation and the elevation of the drain is about 99.5–97.3 or 2.2 feet. The minimum depth occurs at station 41.2, and it is 97.67–97.08 or 0.59 feet. This could be a problem because a drain is only 0.59 feet below the surface. At this depth, it is easily damaged and in colder climates would have problems with freezing.

The reason for fixing the reference for the starting depth and the percent slope data is illustrated in the following section. Spreadsheets are excellent tools for "What if?" scenarios, such as "What if the slope of the drain was changed to 0.5%?" Would the depth be acceptable? The results are shown in Table 1.5 and in Fig. 1.11.

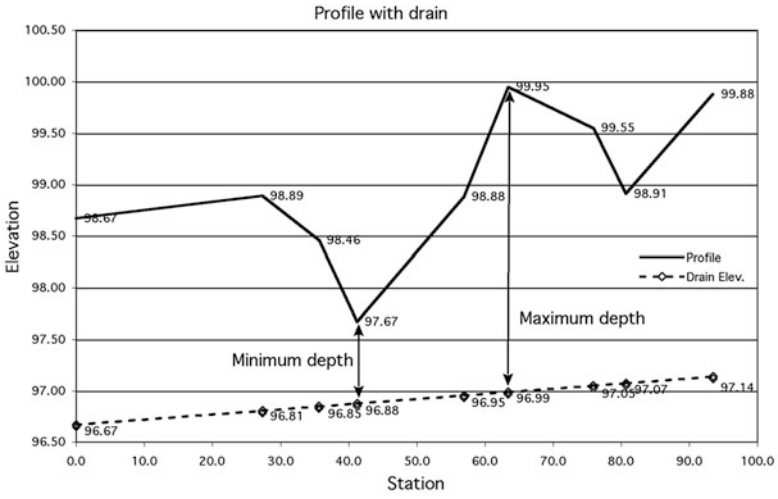

Fig. 1.11 Plot of 0.5% slope drain

The spreadsheet recalculated the depth of the drain for each station by changing the value in cell B3. If a different starting elevation for the drain was desired, changing the value in cell B2 would change the starting depth.

Notice that in this chart, the values for each point were displayed. This is a common option of spreadsheet charts. Changing the slope of the drain from 1% to 0.5% changed the minimum depth at station 41.2 to 0.79 feet, 97.67–96.88 = 0.79. This "What if?" was accomplished by changing one value in the spreadsheet.

Spreadsheets are capable of much more complicated calculations and charts. In addition, they usually have the capabilities of recording "macros" to automate actions that are frequently used and require multiple keystrokes. Another feature of some spreadsheets is the incorporation of a programming language such as Visual Basic. This feature provides tools for the user to write programs and custom functions to manipulate or use data for a specific purpose beyond what is available in the standard spreadsheet functions. This discussion of spreadsheets does not describe all of the capabilities and features of spreadsheets, but it attempts to explain their basic operation and show some of their useful capabilities. It is up to the reader to explore their capabilities in greater depth.

1.3.7 Flow Charts

Flow charts are used to graphically show the relationships of different parts or steps of a process. A common example is the chain of command for a business. They can also be used to display the steps in a manufacturing process. Flow charts use geometric shapes, colors, or other means of defining or providing information about the process. Lines and arrows are used to show direction of flow. The complexity of the flow chart mirrors the complexity of the process being graphed. Flow charts can be categorized by type. Common types are sequential, loop, branch/decision-making, and combination. Flow chart symbols represent different points along the process. An occupation or business may develop specific symbols for their needs, but flow chart users have adopted several common symbols. Figure 1.12 illustrates six of these.

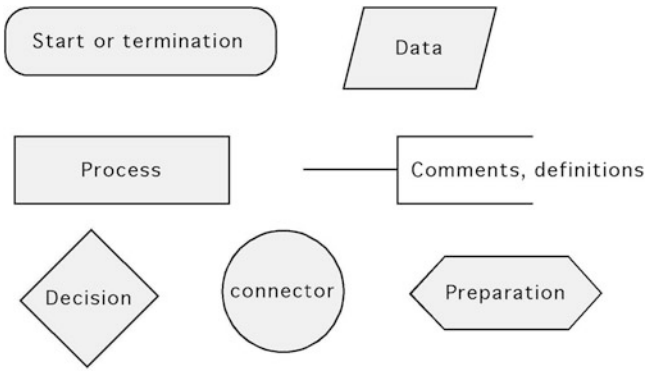

Fig. 1.12 Common flow chart symbols

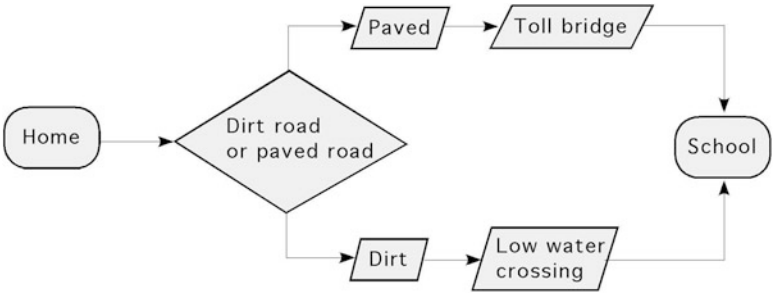

Fig. 1.13 Flow chart example

In addition to different symbols representing different actions, different types of lines and arrows can be used to represent the relationship between the different steps or symbols in the process. The flow chart in Fig. 1.13 shows the alternatives and provides information on each alternative for an individual to travel from home to school.

Flow charts are very useful for visualizing complex processes. The style and appearance of a flow chart is function of the designer.

Chapter 2
Significant Figures and Standard Form

2.1 Objectives

1. Be able to define precision, accuracy, and uncertainty when working with numbers
2. Be able to understand the difference between exact and approximate numbers
3. Be able to determine the number of significant figures
4. Be able to understand a technique for rounding numbers
5. Be able to understand the uses of scientific notation

2.2 Introduction

There is no substitute for a good understanding of significant figures and standard form when solving modern agricultural problems. Before these concepts can be explained, other characteristics of numbers must be understood. Several of these will be explained in the following sections. The first concept is uncertainty.

2.3 Uncertainty

Numerical uncertainty is the amount a recorded value can vary from the true value. A number that is the result of a measurement has uncertainty because measuring tools have a limit in their minimum unit of measure. Some scientific fields state the level of uncertainty after the number, such as 14.5 feet ±0.01. Recording multiple measurements and using the average is one technique for reducing the amount of uncertainty in measurements. One method is presented in Table 2.1. If the uncertainty of a number is not recorded, then assume it is ± half of the smallest unit.

Numbers that are the result of counting do not have uncertainty. A number such as 2 or 4 is exactly 2 or 4. These concepts are explained in more detail in the next section on exact and approximate numbers.

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Table 2.1 Level of uncertainty

Number	Uncertainty
25	± 0.5
15.7	± 0.05
2.567	± 0.0005

Source: *Theory and problems of technical mathematics*, Schaum's outline series, Mcgraw-Hill Book Company, New York, 1979

2.4 Exact and Approximate Numbers

Agriculture uses both exact and approximate numbers. As explained in the previous section, the difference between them is uncertainty. The following sections will explain exact and approximate numbers in more detail.

2.4.1 Exact Numbers

Exact numbers are obtained by counting, by ratios, or by definition. Exact numbers are exact because these numbers have no uncertainty. If you count 10 horses in a pen, you have exactly 10 horses, not 10 and 1/2 horses or 9 and 3/4 horses. A wheel barrow has one wheel, not 1/2 or 2/3 of a wheel. This definition assumes no human error. The number of corn stalks in a mile long row would not be considered an exact number if the number was determined by driving rapidly alongside the row.

Ratios are considered to be exact numbers because 3/4 of a circle is exactly 3/4 of a circle. There is no uncertainty. One note of caution when using ratios, converting ratios to decimal form may convert them to an approximate number. Two thirds, 2/3, is an exact number but its decimal form, 0.6666666..., is an approximate number because the decimal form contains repeating digits. Converting the ratio 3/4 to a decimal does not change it to an approximate number because it is 0.75.

Agriculture also uses numbers that are created by definition. These numbers are exact numbers. By definition 1 h contains 60 min. Used in this fashion 60 min is an exact number. One note of caution, if the value 60 min was the result of a measurement, then it would be an approximate number.

2.4.2 Approximate Numbers

Numbers obtained by measurement or calculations have uncertainty; therefore, they are approximate numbers. The actual value of a measurement has uncertainty because measuring devices only measure to their smallest unit of measurement. For an example of approximate numbers, study Fig. 2.1. The ruler is marked with 1/16 of an inch graduations; therefore, the ruler is only precise to the nearest 1/16 of an inch.

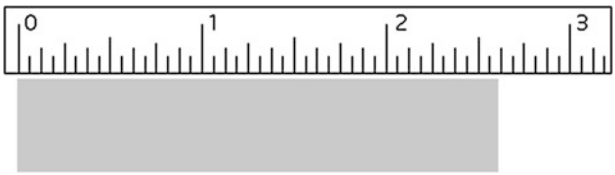

Fig. 2.1 Example of approximate number

In Fig. 2.1, the length of the rectangle is not aligned with a mark on the scale (ruler). The length of the rectangle must be recorded to the nearest shorter reading, 2–9/16 inch, or the next longer reading, 2–5/8 inch. Regardless of the recorded value, the answer is only close to the actual length and thus is an approximate number. If the desire is to reduce the amount of uncertainty in the measurement, then a measuring device with a smaller unit of measure should be used. In this example, a ruler with 1/32 of an inch graduations would produce a measurement with less uncertainty.

Numbers developed from calculations can have uncertainty because digits that are not significant may be retained. Digits can be introduced into problems, which are not accurate (significant). If these digits are included, the accuracy of the answer may decrease with every computation. The potential for error is especially great if a calculator or spreadsheet is used because they carry 20 or more digits in memory, regardless of their significance to the problem. When multiple calculations are completed using either a calculator or computer, each computation can introduce numbers that are not significant. The task is to determine how many digits are significant and to round accordingly.

The concepts of exact and approximate numbers also influence other characteristics of numbers. Two of these are precision and accuracy. Exact numbers have no uncertainty; therefore, they are precise and accurate. This is not true for approximate numbers.

2.5 Precision

Precision must be considered when using approximate numbers. The term precision can relate to the unit of measure or the scatter in the data. A smaller unit of measure is more precise than a larger unit of measure. For example, a sack of feed weighed on a scale that measures to the nearest 10 pounds has less precision than if the feed was weighed on a scale capable of measuring to the nearest 5 pounds. A micrometer that measures to a thousandth of an inch is much more precise than a carpenters tape with 1/8 of an inch as the smallest measure.

Physics uses a variation of unit of measure. When taking multiple measurements of a value, not all of the measurements will be exactly the same. This difference is called scatter. Measurements with a small amount of scatter are precise. If several

darts are thrown at a target and they all land very close together in a tight group, the throws were precise. The tie-in with the previous explanation of precision is that a small unit of measure tends to restrict the amount of scatter that can occur. Using the previous example, recording measurements with the micrometer that measures to 1/1000 ths of an inch will limit the scatter to plus or minus 0.001 inch. The scatter of the tape a tape that measures to 1/8 th of an inch is plus or minus 1/8 of an inch, 0.125.

2.6 Accuracy

Accuracy in approximate numbers can also be explained in different ways. One way to explain accuracy is referring to the number of decimal places obtained in the answer. Increasing the number of decimal places increases the accuracy. A measurement of 12.15 feet is more accurate than a measurement of 14.4 feet.

A related interpretation of accuracy is an evaluation of how close a group of measurements are to the true value. Continuing the analogy of throwing darts, if the darts land close to the center of the target, the throws were accurate even without a tight grouping.

2.7 Significant Figures

The principle of significant figures is important in problem-solving because calculators and computers can artificially increase the precision of a number. Calculators routinely carry 20 or more decimal places on screen and/or in memory even though the accuracy and precision of measurements could be only two or three places. It is usually necessary to determine the number of digits that should be kept in a number after mathematical computations and round the answer. The rules for determining significant digits are different for exact and approximate numbers.

Because there is no uncertainty with exact numbers, all of the digits are considered to be significant. When rounding answers produced with exact numbers, assume the answer has the same number of significant figures as the largest exact number used in the calculations.

Determining significant figures for approximate numbers is more complicated. The first issue is the significance of zeros. A common practice is to consider a zero significant if it is between two nonzero numbers, between a non-zero number and decimal point or a trailing zero to the right of the decimal point. For example, 540.2 has four significant figures, and 5400.2 has five significant figures. An example of trailing zeros to the right of the decimal point is 0.03250. It has four significant digits. The number 0.3250 has four significant digits. The number 0.0325 has three significant digits.

A zero to the left of the decimal point is not considered significant when it is the last number and there is no decimal point. For example, the number 540 has two significant figures. An exception to this rule is when the zero is the result of rounding. The number 459.8 rounded to three significant figures is 460. In this case, the zero is considered significant. The problem is without additional information the reader doesn't know if the zero is the result of rounding. In this case, the significance of the zero can be ambiguous. The use of a trailing decimal such as "460." is one way of denoting significance of trailing zeros, but scientific notation is more commonly used to increase clarity. Scientific notation is discussed in more detail later in this chapter.

For nonzero numbers, the number of significant digits for an approximate number depends on the precision of the measuring instrument. If you are given the weight of a steer as 551 pounds and know that the scale measured to the nearest 0.1 pounds, then the actual weight could be less than 551.1 but more than 550.9 pounds and be recorded as 551 pounds. The number will have four significant figures. To be correct, if the weight of the steer was actually 551 pounds, the number should have been written as 551.0.

When the precision of the measuring instrument is not known, determining significant figures is much more difficult. A common practice is to assume the precision is +/− one half of the smallest unit in the number. For example, a distance of 347 feet would have four significant figures because the measurement could be between 347.4 and 346.6 feet and be recorded as 347 feet.

Problem You are helping measure the weight of a calf on scales that measure to the nearest 0.5 pound. You are told the calf weighs 102 pounds. How many significant figures does the weight have?

Solution The number of significant figures is four. The scale can read 101.5, 102.0, or 102.5. If the pointer on the scale is between 101.5 and 102.0 but closer to 102.0, then the reading is recorded as 102.0. Similarly, if the pointer is between 102.0 and 102.5 but closer to 102.0, then reading is recorded as 102.0. If the weight is exactly 102 pounds, the weight of the calf should be recorded as 102.0 pounds. Then the weight has four significant digits.

Problem What is the area (ft^2) of a room if the width is 12 ft 3 in and the length is 22 ft 3/16 in?

Solution The first step is to convert the dimensions to decimal form, 12 ft 3 in = 12.25 ft and 22 ft 3/16 in = 22.1875 ft. Completing the multiplication gives a value of 271.79687 ft^2. How many digits are significant?

Two rules have been developed to help determine the number of significant digits during mathematical computations.

- Adding or subtracting: the answer should be rounded to the number of decimal places in the least precise number.
- Multiplication and division: the answer should be rounded to the number of significant figures in the least accurate number.

For this problem, rule number two applies. The product, 271.79687, is reduced to four significant figures because 12.25 feet has four significant figures. The correct area for the room is 271.8 ft^2.

Problem You need to know the perimeter of the room to calculate the amount of paint needed to paint the walls. The dimensions of the floor are 12.25 feet by 12.1875 feet.

Solution In this case, the perimeter is the sum of the lengths of the four walls in the room, $P = 12.25 + 12.25 + 22.1875 + 22.1875$. For this problem, rule one applies. The sum, 68.1750, is reduced to four significant figures. The answer is 68.18 ft.

2.8 Rounding Numbers

Rounding is used to eliminate figures that are not significant. When the digits to be rounded are to the left of the decimal point, zeros replace the digits. For example, if you need to reduce the area of an acre, 43,560 ft^2, to two significant digits, the answer is 44,000 ft^2. When the digit being dropped is greater than 5, add one to the next digit remaining. When the digit being dropped is less than 5, the first remaining digit is unchanged. If the digit being dropped is exactly 5, leave the remaining digit even. When the remaining digit is odd, add one. For example, if the number 43,560 is rounded to one significant digit, the answer is 40,000; rounded to two, it is 44,000, and rounded to three, it is 43,600.

2.9 Scientific Notation and Standard Form

Scientific notation and standard form were developed to express large or small numbers in a more convenient form. Initially, they were primarily used with slide rules because three significant digits was the practical limit that could be carried on a slide rule. The need for reducing numbers to three digits is not as relevant for calculators and computers, but knowing scientific notation and standard form is useful for estimating answers and for recording very large or very small numbers with only a few significant figures.

Scientific notation and standard form use powers of ten to replace the nonsignificant digits of large or small numbers. Standard form uses a whole digit, then a decimal point, and two significant figures. Scientific notation uses the same format. The difference is that in scientific notation, the number of significant figures is not limited to three. For example, if the number 1,000,000 has two significant figures, it is expressed as 1.0×10^6. This number is read as "one point zero times ten to the sixth power." The number 43,560,000 expressed in scientific notation with four significant figures would be 4.356×10^7. To use scientific notation effectively, you

must understand the powers of numbers and how they can be manipulated during mathematical computations.

First a review of the powers of ten:

$$\begin{aligned} 10^0 &= 1 \\ 10^1 &= 10 \qquad & 10^{-1} &= 0.1 \text{ or } \frac{1}{10} \\ 10^2 &= 100 \qquad & 10^{-2} &= 0.01 \text{ or } \frac{1}{100} \\ 10^3 &= 1{,}000 \qquad & 10^{-3} &= 0.001 \text{ or } \frac{1}{1{,}000} \\ 10^4 &= 10{,}000 \qquad & 10^{-4} &= 0.0001 \text{ or } \frac{1}{10{,}000} \end{aligned}$$

There are several helpful rules to use when working with powers of 10:

- When a number 10 and its exponent are moved from the denominator of a fraction to the numerator, or from the numerator to the denominator, the sign of the exponent changes. Thus:

$$\frac{1}{10^{-3}} = \frac{10^3}{1} \text{ and } \frac{10^{-4}}{1} = \frac{1}{10^4}$$

- When two or more numbers in standard form are multiplied together, the powers of 10 can be added. Thus:

$$\begin{aligned} 10^3 \times 10^5 &= 10^{(3+5)} = 10^8 \\ 10^5 \times 10^{-2} &= 10^{(5+(-2))} = 10^3 \\ 10^{-4} \times 10^{-3} \times 10^4 &= 10^{((-4)+(-3)+4)} = 10^{-3} \end{aligned}$$

  It is important to note that several different methods are used to express scientific notation. One method replaces the 10 and exponent with an "E" and the power of ten:

$$4.0\text{E}3 \times 5.0\text{E}5 = 20\,\text{E}^{3+5} = 20.0\text{E}8$$

  Another method reduces the confusion of using an "x" to represent both multiplication and powers of ten by replacing the "x" for multiplication with a • :

$$4.0 \bullet 10^3 \times 5.0 \bullet 10^5 = 20 \bullet 10^{3+5} = 20 \bullet 10^8$$

  Other methods are also used.

- When two or more numbers in standard form are divided, the powers of 10 are subtracted. Thus:

$$\frac{10^4}{10^3} = 10^1 \text{ or } 10 \qquad \frac{4 \bullet 10^4}{2 \bullet 10^2} = 2 \bullet 10^2$$

$$\frac{10^{-4}}{10^2} = 10^{-6} \qquad \frac{4 \bullet 10^{-4}}{2 \bullet 10^2} = 2 \bullet 10^{-6}$$

- When two or more numbers in standard form are added or subtracted, the numbers must be converted to the same power of 10, and the power of 10 is not affected during the addition or subtraction. Thus:

$$4 \bullet 10^4 - 3 \bullet 10^3 \text{ Becomes } \frac{\begin{array}{r} 40 \bullet 10^3 \\ -3 \bullet 10^3 \end{array}}{37 \bullet 10^3} = 3.7 \bullet 10^4$$

and

$$4 \bullet 10^4 + 3 \bullet 10^3 \text{ Becomes } \frac{\begin{array}{r} 40 \bullet 10^3 \\ +3 \bullet 10^3 \end{array}}{43 \bullet 10^3} \text{ or } 4.3 \bullet 10^4$$

Chapter 3
Common Units of Measure

3.1 Objectives

1. Be able to explain the different U.S. customary units of measure
2. Be able to convert from one unit of measure to another
3. Be able to use the units associated with each measurement
4. Be able to calculate horsepower
5. Be able to explain the SI measurement system
6. Be able to explain differences between weight, force, and mass

3.2 Introduction

All measurements require a unit to define the magnitude of the quantity. One of the factors that determine the preferred unit is the magnitude of the measured variable. For example, in the customary system, if the distance is large, the preferred unit is the mile. When the distance is very small, the preferred unit could be in decimal inches or fractions of an inch. The units of measure can be divided into several categories. The common categories used in agriculture are:

1. Distance
2. Area
3. Temperature
4. Volume
5. Weight or force
6. Pressure
7. Time
8. Velocity
9. Torque power
10. Power

3.3 Systems of Units

Modern agriculture uses two systems of units, the US customary system (sometimes called the English or gravimetric system) and the metric or SI system. Both of these systems will be discussed in this chapter.

The basis for many of the units of measure in the U.S. customary system are lost in history. The US Bureau of Weights and Measures has the responsibility of

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storing and maintaining the standards for all of the U.S. customary units of measures. They have the standard foot, the standard yard, the standard pound, etc. All of the measuring devices used in the United States are based on one of these standards.

3.4 Distance (D)

The dimension of distance has two common meanings, displacement and length. Displacement is the movement from one point to another. If you walk one mile, you have displaced a distance of 5280 feet. Length refers to the physical size of an object. For example, the lengths of a standard piece of paper are 8.5×11 inches. The common units for distance are inches (in), feet (ft), yards (yd), and miles (mi).

3.5 Area

The unit of area is defined as the number of unit squares equal in measure to the surface. This indicates that an area is a surface and the size of the surface is measured in terms of units squared. The common units for area are the units for distance squared, in^2, ft^2, $miles^2$, etc. Agriculture uses the acre (ac) as the unit for large land areas. There are 43,560 ft^2 in one acre.

3.6 Temperature

Temperature is the degree of hotness or coldness of an object. Five different measures of temperature have been used. The customary unit of temperature is the degree Fahrenheit.

3.7 Volume

Volume is defined as the amount of space occupied by a three-dimensional figure. The basis for a volume is a distance cubed in^3, ft^3, etc. In the U.S. customary system of weights and measures, additional units of volume are also used, such as gallon, quart, pint, and cup. The U.S. Bureau of Weights and Measures has standardized the quantity of each one of these units in terms of distance cubed. For example, there are 231 in^3 in one gallon (see Appendix I) for further conversion factors.

3.8 Weight

Weight is defined as the force of gravity acting on an object. The common units for weight are ounces, pounds, and tons in the U.S. customary system.

3.9 Force (F)

Force is that action which causes or tends to cause motion or a change of motion of an object. To describe a force completely, its direction of action, magnitude, and point of application must be known. What is commonly referred to as a “force” is

really two forces, as forces are never present singly but always in pairs. The two parts are called action and reaction. They are always of equal magnitude but in opposite directions. In this text, the weight of an object will be considered a force. Forces are commonly measured in units of ounces (oz), pounds (lb), and tons (ton) in the U.S. customary system.

3.10 Pressure

Pressure is the amount of force or thrust exerted over a given area. Pressure is the combination of two units, force, and area. Therefore, the U.S. customary units for pressure will be a combination of these two, lb/in^2, oz/in^2, lb/ft^2, etc.

3.11 Time (T)

The concept of time has its root in the natural cycles of the earth. One very visible cycle is the ocean tides. The words time and tide both come from the same root. The current idea of time is as a measure of an interval of duration. Time may be better described as an accounting technique for relating events. The common units for time are seconds (sec), minutes (min), and hours (hr).

3.12 Velocity

Velocity is the time rate of movement. Velocity is also a combined unit. It is the combination of distance and time. The common units of velocity are ft/min, mi/hr, etc.

3.13 Power (P)

Power is the rate of doing work. The term rate includes the concept of time, and work. Work (W) is the result of a force acting (or moving) through a distance. To understand power, it is necessary to understand work. Written as an equation:

$$\text{Work } (W) = \text{Distance } (D) \times \text{Force } (F)$$

A numerical value for work may be obtained by multiplying the value of a force by the displacement.

Problem Determine the amount of work produced when a force of 100.0 pounds displaces 12.0 feet.

Solution

$$\begin{aligned} W &= D \times \text{F} \\ &= 12.0 \text{ ft} \times 100.0 \text{ lb} \\ &= 1200.0 \text{ ft-lb or } 1.2 \text{ E3} \end{aligned}$$

In this situation, 1200 foot pounds of work was completed. Notice that according to this definition, unless both displacement and force occur, no work is being accomplished.

Problem A loaded wagon weighing 10,000.0 pounds requires 400.0 pounds of force to pull it along a horizontal surface. How much work is done if the wagon is pulled for 100.0 feet? (In this example, we assume that rolling resistance equals zero.)

Solution

$$\begin{aligned} W &= D \times F \\ &= 100.0 \text{ ft.} \times 400.0 \text{ lb.} \\ &= 40{,}000.0 \text{ or } 4.0 \text{ E4 ft-lb.} \end{aligned}$$

In this problem, the 40,000 pounds of force is not related to the weight of the wagon. It is the force required to pull the wagon.

The equation for power is:

$$\text{Power} = \frac{\text{Work}}{\text{Time}} \quad \text{or} \quad P = \frac{W}{T}$$

because work equals distance times force. The power equation can be written as:

$$\text{Power} = \frac{\text{Force} \times \text{Distance}}{\text{Time}} \quad \text{or} \quad P = \frac{F \times D}{T}.$$

Distance divided by time, D/T, equals velocity (speed); therefore, power can also be calculated by multiplying force times the velocity. This demonstrates that power is a combination of distance, force, and time.

Problem How much power is developed when a force of 100.0 pounds moves through a distance of 12.0 feet in 2.0 min?

Solution

$$P = \frac{D \times F}{T} = \frac{12.0 \text{ ft} \times 100.0 \text{ lb}}{2.0 \text{ min}} = \frac{1200.0 \text{ ft-lb}}{2.0 \text{ min}} = 600.0 \text{ or } 6.0 \text{ E2} \ \frac{\text{ft-lb}}{\text{min}}$$

Notice that the unit associated with power is a combination of the individual units for the variables. In this case, the answer is read as "600 foot pounds per minute." This is the "time rate" at which work is being done. Remember; always write down the units that are associated with a number.

Problem A person loaded a 60.0 pound bale onto a 4.0 feet high truck platform in 0.50 min. How much power was developed?

Solution

$$P = \frac{D \times F}{T} = \frac{4.0 \text{ ft} \times 60.0 \text{ lb}}{0.50 \text{ min}} = \frac{240.0 \text{ ft-lb}}{0.50 \text{ min}} = 480 \ \frac{\text{ft-lb}}{\text{min}}$$

Up to this point, we have used easy-to-understand values with units of feet for distance, pounds for force, and minutes for time. Suppose that in the previous problem the individual could load three 60.0 pound bales in 0.50 min. In this example, it is easy to make a mistake in determining a value for the force. The solution to this problem is:

$$P = \frac{4.0 \text{ ft} \times \dfrac{3 \text{ bales}}{1} \times \dfrac{60.0 \text{ lb}}{\text{bale}}}{0.50 \text{ min}} = \frac{720 \text{ ft-lb}}{0.50 \text{ min}} = 1400 \ \frac{\text{ft-lb}}{\text{min}}$$

Here, the power produced is 1400 ft-lb/min because the weight moved in 0.50 min is the weight of all three bales (3 × 60 lb).

This problem illustrates a principle of power. If three times the amount of work is done in the same amount of time, the power will be increased three times. What is the impact on the power produced if the distance changes or if the time changes?

Problem If a person could load three 60.0 pound bales onto the 4.0 foot platform in 10.0 s, instead of 0.50 min, how would this change the power produced?

Solution

$$P = \frac{D \times F}{T} = \frac{4.0 \text{ ft} \times 180.0 \text{ lb}}{10.0 \text{ sec}} = 720 \frac{\text{ft-lb}}{\text{sec}} = 72 \frac{\text{ft-lb}}{\text{sec}}$$

The amount of power changed, but this answer cannot be compared to the previous one because the units are different. You might ask, is foot-pounds per second an acceptable unit of measure for power? Yes, but to compare this value for power to the previous answer, the units must be converted. This can be accomplished in several ways. When the desired units are ft-lb/min and the value is in units of ft-lb/sec, a conversion value can be added to the equation. To change the unit of time from seconds to minutes:

$$P = \frac{4.0 \text{ ft} \times 180.0 \text{ lb}}{10.0 \text{ sec} \times \frac{1 \text{ min}}{60.0 \text{ sec}}} = \frac{720 \text{ ft-lb}}{0.166\ldots \text{min}} = 4320 \text{ or } 4300 \frac{\text{ft-lb}}{\text{min}}$$

Now the two values can be compared. It should be obvious that it takes a greater amount of power to complete the same amount of work in less time. A similar relationship is true for the distance moved. The power requirement will change as the distance moved changes, assuming that the force and the time remain the same.

In summary, power is directly proportional to distance and force and is inversely proportional to time.

In working with agricultural machinery, speed usually is measured in miles per hour (mph). When this is the case, the units must be changed. Otherwise, the answer will be incorrect. Study the following statements:

If power is equal to work divided by time, then $P = \frac{F \times D}{T}$. This can be changed to $P = F \times \frac{D}{T}$ and because D/T (distance/time) is velocity, if D/T is in miles/hour, it must be converted to feet/minute. The common conversion factor for speed is 1 mph = 88 ft/min. This factor is obtained as follows:

$$88 \frac{\text{ft.}}{\text{min.}} = \frac{5280 \text{ ft.}}{1 \text{ mi.}} \times \frac{1 \text{ hr.}}{60 \text{ min.}} \times \frac{1 \text{ mi.}}{1 \text{ hr.}}$$

Therefore, power can also be found by:

$$P = F \times S \times 88$$

where F = force (lb); S = speed (mi/hr); 88 = units conversion value.

3.14 Torque (T_o)

Torque is the application of a force through a lever arm. It is a force that causes or tends to cause a twisting or rotary movement. In equation form:

$$\text{Torque} = \text{Force} \times \text{Lever arm length}$$

or:

$$T_o = F \times LA$$

where T_o = torque (lb-ft or lb-in); F = force (lb); LA = lever arm length (ft or in).

Because force is measured in pounds and length in feet or inches, the common units of torque are pound-feet (lb-ft) or pound-inches (lb-in).

Problem How much torque is developed when a 50.0 pound force is applied at the end of a wrench that is 1.0 foot long?

Solution

$$T_o = F \times LA = 50.0 \text{ lb} \times 1.0 \text{ ft} = 50 \text{ lb-ft}$$

Notice that the answer has been written as "50 pound-feet." To distinguish torque from work, torque is written with units with the force unit first, "pound-feet," and the units for work are written with the distance unit first, "foot-pounds."

There is one additional difference between torque and work. It was stated earlier that unless there is movement, there is no work. Because torque is a force working through a lever arm, torque can exist without movement.

Problem Which of the following will cause a greater torque to be exerted on a shaft: (1) 50.0 pounds of force applied at the end of a 6.0 inch wrench or (2) 15.0 pounds of force applied at the end of a 24.0 inch wrench?

Solution

$$1.\ To_1 = 50.0 \text{ lb} \times 0.5 \text{ ft} = 25 \text{ ft} - \text{lb}$$
$$2.\ To_2 = 15.0 \text{ lb} \times 2.0 \text{ ft} = 30 \text{ lb} - \text{ft}$$

Situation (2) will cause greater torque (twisting effect) on the shaft.

3.15 Horsepower (HP)

Although power is a basic unit, in agriculture, the more common unit is horsepower. Several different measures of horsepower are used. For example, when discussing tractors, you may use engine horsepower, brake horsepower, drawbar horsepower, or power take-off horsepower.

The following section will investigate the principles of horsepower. Horsepower is an arbitrary unit developed by James Watt to promote his early steam engines. The historical story is that he watched horses pulling loads of water out of mine

shafts. He wanted a way to compare the effort of different horses. He concluded that one horsepower was equal to performing work at the rate of 33,000 foot-pounds per minute. Expressed algebraically, the conversion from power to horsepower is:

$$1\text{ hp} = \frac{\text{Power}\dfrac{\text{lb-ft}}{\text{min}}}{33{,}000\dfrac{\text{lb-ft}}{\text{min}}} \text{ or } 1\text{ hp} = \text{Power}\frac{\text{lb-ft}}{\text{min}} \times \frac{1\text{ min}}{33{,}000\text{ lb-ft}}$$

Note that unless power is in the units of ft-lb/min, the use of the conversion factor 1 hp = 33,000 ft-lb/min will not produce correct results. The common horsepower equation is:

$$\text{hp} = \frac{F \times D}{T \times 33{,}000}$$

This is an example of an equation with a conversion constant. This means all of the variables must have the correct units. This equation requires distance (D) expressed in feet, force (F) in pounds, and time (T) in minutes.

Problem How many horsepower are developed if a person loads six 60 pound bales onto a truck platform 4.0 feet high in 1.5 min?

Solution

$$\text{hp} = \frac{F \times D}{T \times 33{,}000} = \frac{4.0\text{ ft} \times \left(6\text{ bales} \times 60.0\dfrac{\text{lb}}{\text{bale}}\right)}{1.5\text{ min} \times 33{,}000} = \frac{1440}{49{,}500}$$
$$= 0.02909\ldots \text{ or } 0.029\text{ hp}$$

What would happen if the time required to load the hay in the example is measured as 90.0 seconds instead of 1.5 minute. Obviously 90.0 second equals 1.5 minute, but if the same equation is used either the seconds must be converted to minutes or a different conversion factor from power to horsepower must be used. If the 33,000 conversion unit is used with time measured as 90.0 seconds, the answer will be incorrect. The problem can be solved in two different ways. The first way is to add a conversion unit for time to the equation. This would be the preferred method for just a few calculations.

$$\text{hp} = \frac{F \times D}{T \times 33{,}000} = \frac{4.0\text{ ft} \times \left(6\text{ bales} \times \dfrac{60.0\text{ lb}}{\text{bale}}\right)}{\left(90.0\text{ sec} \times \dfrac{1\text{ min}}{60\text{ sec}}\right) \times 33{,}000} = \frac{1440\text{ ft-lb}}{49{,}500}$$
$$= 0.02909\ldots \text{ or } 0.029\text{ hp}$$

The second way is to determine the appropriate conversion value for the units being used. In a situation where horsepower will be calculated several times and time is measured in seconds, it would be more efficient to use a conversion value

from power to horsepower appropriate for when time is measured in seconds instead of minutes. This can be accomplished using unit cancellation:

$$\frac{\text{ft-lb}}{\text{sec.}} = \frac{33{,}000\ \text{ft-lb}}{1\ \text{min.}} \times \frac{1\ \text{min.}}{60\ \text{sec.}} = 550\frac{\text{ft-lb}}{\text{sec.}}$$

Using this conversion value, the previous problem can be solved by:

$$\text{hp} = \frac{F \times D}{T \times 550} = \frac{1440\ \text{ft-lb}}{90.0\ \text{sec.} \times 550} = \frac{1440}{49{,}500} = 0.02909\ldots \text{or } 0.029\ \text{hp}$$

Horsepower can also be calculated using torque and the speed of the shaft. This is called shaft horsepower. This equation was used to evaluate the horsepower being produced by early engines using a Prony Brake (Fig. 3.1).

Early Prony Brakes used the friction between a rotating flywheel and a stationary block of wood to produce a force on the lever. Once the force on the lever and the speed of rotation of the flywheel is known, the brake horsepower can be determined. Mathematically, brake horsepower is:

$$\text{Bhp} = \frac{\text{FLN}}{5252}$$

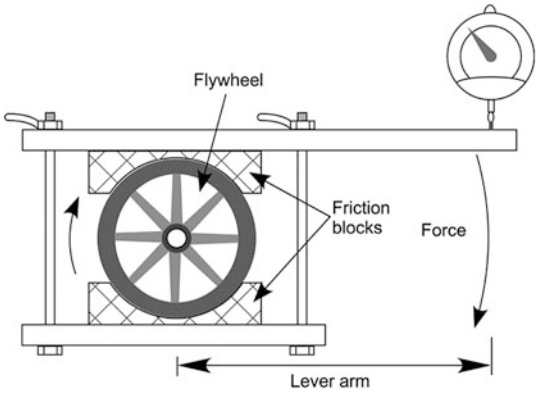
where F = force produced (lb); L = length of the lever arm (ft); N = rotary speed of the Prony brake shaft (rpm); 5252 = units conversion constant.

This equation is derived from the horsepower equation:

$$1\ \text{hp} = \frac{\frac{2\pi}{\text{rev}} \times F \times D \times N}{\frac{1\ \text{hp}}{33{,}000\ \frac{\text{ft\_lb}}{\text{min}}}} = \frac{F \times D \times N}{5252}$$

where the length of the lever arm equals the radius of the circle and the distance the force is working through.

Fig. 3.1 Prony Brake



Problem Determine the horsepower being produced when 8 pounds of force is measured at the end of an 18.0 inch Prony brake arm when the flywheel is rotating at 1700 revolutions per minute?

Solution

$$\begin{aligned}\text{Bhp} &= \frac{\text{FLN}}{5252} = \frac{8\text{ lb.} \times \left(18.0\text{ in.} \times \frac{1\text{ ft.}}{12\text{ in.}}\right) \times 1700\ \frac{\text{rev.}}{\text{min.}}}{5252} \\ &= \frac{244{,}800}{5252} \\ &= 3.8842 \ldots \text{ or } 3.9\text{ hp}\end{aligned}$$

[Note: the answer was rounded to two significant figures because the significance of the zeros in 1700 are ambiguous, but at least two significant figures should be used because 8 pounds is a measurement and the uncertainty is ±0.5 pounds.]

Brake horsepower contains a length and a force. Earlier discussions explained that force times a length is torque. Therefore, the brake horsepower equation can be rewritten to use torque:

$$\text{Bhp} = \frac{T_o \times N}{5252}$$

A Prony brake can still be used to measure the horsepower of engines, but electrical and hydraulic dynamometers are more accurate than the Prony brake. The rotary power of modern engines is measured by connecting directly the power take-off (pto) shaft.

3.16 Using Units in the Metric (SI) System

A major problem with U.S. customary units is their lack of logical relationship between units. For instance, there is no obvious reason why the standard mile is 5280 feet. The metric system was created in the late eighteenth century by the French to address this problem.

One of the advantages of the SI system is that all of the units are based on natural phenomena. For example, a meter is the distance light travels, in a vacuum, in 1/299,792,458th of a second. The US agricultural industry is based on the customary units of measure; however, many manufactures are converting to SI units, and agriculture has become more international in buying and marketing products. It is critical to understand the differences between the two systems.

In the previous section, several U.S. customary units of measure were discussed. The following section will explain the comparable units in the SI system. The SI system is a decimal-based system. To use the different units requires knowing the prefixes used for the different powers of 10 (Table 3.1).

Although the recommended practice in the metric system is to use standard units or 1000 unit multiples of the units, the SI system also has nonstandard units. It is

Table 3.1 Prefixes for SI units

Yotta [Y]	$= 10^{24}$	Yocto [y]	$= 10^{-24}$
Zetta [Z]	$= 10^{21}$	Zepto [z]	$= 10^{-21}$
Exa [E]	$= 10^{18}$	Atto [a]	$= 10^{-18}$
Peta [P]	$= 10^{15}$	Femto [f]	$= 10^{-15}$
Tera [T]	$= 10^{12}$	Pico [p]	$= 10^{-12}$
Giga [G]	$= 10^{9}$	Nano [n]	$=10^{-9}$
Mega [M]	$= 10^{6}$	Micro [μ]	$= 10^{-6}$
Kilo [k]	$= 10^{3}$	Milli [m]	$= 10^{-3}$
Hecto [h]	$= 10^{2}$	Centi [c]	$= 10^{-2}$
Deca [da]	$= 10$	Deci [d]	$= 0.1$

critical to understand and correctly apply the differences between the US customary and the SI system (Appendix II).

3.16.1 Distance

The standard unit of distance in the SI system is meter. A meter is about 39 inches. The other lengths that are commonly used are the millimeter (mm), the centimeter (cm), and the kilometer (km).

3.16.2 Area

The principle of area for SI units is the same as customary units. It is two distances multiplied together. The units become millimeters squared, etc. In the customary system, the standard unit of land measurement is the acre. In the SI units, it is the hectare. An acre is about 0.4047 hectares.

3.16.3 Temperature

In the SI system, the preferred unit for measuring temperature is Celsius. The Celsius scale was established to place the boiling point of water at 100 °C and the freezing point at 0 °C. The equation for converting from the Fahrenheit scale to the Celsius scale is:

$$T_C = \frac{5}{9} \times (T_F - 32)$$

and the conversion from Celsius to Fahrenheit is:

$$T_F = \frac{9}{5} \times (T_C + 32)$$

3.16.4 Volume

The standard unit of volume for the SI system is liter. A liter is defined as 1000 cubic centimeters. A liter is slightly larger than a quart.

3.16.5 Weight and Force (Mass)

The US customary system (sometimes referred to as a gravitational system) is a force-based system, and the SI is mass-based system. The key to understanding how to solve problems in these two systems is to understand the relationship between mass and force. The definition of mass was proposed by Sir Isaac Newton.

One useful definition of mass (Hibbler, R.C. Engineering Mechanics 6th Edition. Macmillan, New York) is "Mass is a property of matter by which we can compare the action of one body with that of another. This property manifests itself as a gravitational attraction between two bodies and provides a quantitative measure of the resistance of matter to a change in velocity." This implies several things. Gravity is a form of acceleration. Thus, mass is independent of gravity. This means that your mass is the same on the earth, moon, or in rocket ship leaving the earth. Your mass is also the same in space orbiting the earth.

Mass can be determined by comparing an object of known mass to your object whose mass is not known. One way to do this is to place the object with the unknown mass in one pan and add objects of known mass in the other pan until the scale is balanced. Gravity is the acceleration acting on both pans of the balance scale. The balance scale will give the same results in the rocket ship, on earth, or on the moon.

Force or weight changes with gravity or acceleration. You will weigh about 1/6 as much on the moon as on the earth, because the force attracting you to the moon's gravity is about 1/6 that of the earth's gravity. In orbit about the earth, where the net gravitational force is zero, your weight is zero.

In this book we are primarily interested in force rather than mass. Sir Isaac Newton's second law defines the relationship among mass (m), acceleration (a), and force (F). This equation is: $F = m \times a$

The SI unit of force is the newton (N), the unit of mass is the kilogram, and the unit of acceleration is meter/second^2 (m/s^2). In the SI system, the mass of the body is specified, and the force is caused by gravity. In the SI system, we specify the mass of the object and calculated the weight. Since gravity is a form of acceleration, we can rewrite Newton's second law as:

$$W = m \times g$$

where W is the weight in newton (N) and g is the acceleration by gravity at the earth's surface, 9.81 (m/s^2).

In the U.S. customary system, we measure the force in pounds and calculate the mass. The unit of mass in the U.S. customary systems is the slug. Mass is calculated by:

$m = \dfrac{W}{g}$ where W is the weight in pounds (lb) and $g = 32.3$ ft/s^2.

The relationship of mass and weight can be explained using an example of a pry bar, a class one lever. A block of wood is placed next to the rock, and the bar is placed on top of the wooden block and under the rock. You push down on the end of the bar with enough force to raise your feet off the ground, and the rock doesn't move. You have recently "weighed" yourself with a metric scale, and your mass is 81 kg. The distance from the wooden block to your hands, force arm length, is

1.5 m, and the distance from the wooden block to the middle of the mass of the rock, resultant arm length, is 0.3 m. What is the weight of the rock?

The first step in determining the weight of the rock is to convert your body mass to weight in newton (N).

$$W = m \times g$$

$$W = 81 \text{ kg} \times 9.81 \frac{\text{m}}{\text{s}^2} = 794.61 \frac{\text{kg} \bullet \text{m}}{\text{s}^2} = 795 \text{ N}$$

The second step is to calculate the weight of the rock using the formula for a class one lever and solving for F_r:

$$F_a \times A_a = F_r \times A_r$$

The equation for a class one lever is written in terms of a force, but weight is a force so $F_A = W$:

$$F_r = W \times \frac{A_a}{A_r}$$

$$F_r = 795 \text{ N} \times \frac{1.5 \text{ m}}{0.3 \text{ m}} = \frac{1192.5}{0.3} = 3975 \text{ or } 4000 \text{ N}$$

The weight of the rock is greater than 4000 N or 4 kN.

3.16.6 Pressure

Pressure is force per unit area. In the SI system, a combination of force and area can be used, but the preferred unit is a newton per meter squared (N/m^2) which is commonly called a Pascal (Pa). Therefore,

$$1 \frac{\text{N}}{\text{m}^2} = 1 \text{ Pa}$$

3.16.7 Time

The units used to measure time are the same for both the U.S. customary and SI units.

3.16.8 Velocity, Speed, and Acceleration

Velocity and speed are measured by determining a distance and the time it takes to travel the distance. The standard unit for distance in the SI system is meters, and the standard unit for time is seconds; therefore, the SI units for velocity are meters per second (m/s). Acceleration is the rate at which velocity changes. The units in the SI system are m/s/s or m/s^2. The units of acceleration in the U.S. customary system are ft/s/s or ft/s^2.

3.16.9 Power

Power is the rate of doing work, and work is force times a distance. In the SI system, force is measured in units of newton and distance in meters. This means work is

measured in units of newton · meters. This is an acceptable unit of measure for work, but for many calculations, the preferred unit is the joule. One joule is the amount of work done when an applied force of 1 newton moves through a distance of 1 m in the direction of the force.

The units of time in the SI system are the same as the customary system. In the SI system, power is measured in units of joules per second. Measuring power in units of joules per second is correct, but the preferred unit is the watt (W). One watt is equal to 1 joule per second.

3.16.10 Torque

Torque is a measure of a force working through a lever arm. In the SI system, force is measured in newtons, and distance is measured in meters. The units for torque are: newton · meters (N · m).

3.16.11 Horsepower

The SI unit system does not have a comparable conversion from power to horsepower. In the SI system, watts are used to measure all forms of power.

Chapter 4
Simple Machines

4.1 Objectives

1. Be able to explain the common simple machines
2. Be able to give an example of each type of simple machine
3. Be able to use the principles of simple machines to solve problems

4.2 Introduction

A machine is any device that either increases or regulates the effect of a force or produces motion. All agricultural machines are composed of combinations and modifications of two basic machines, the lever and the inclined plane. We will study the basic principles surrounding these two machines and illustrate some of their common modifications and uses. (*Note*: in the following discussion of simple machines, two assumptions are made: losses due to friction are ignored, and the strength of the materials is not considered.)

4.3 Lever

A lever is a rigid bar, straight or curved, capable of being rotated around a fixed point called a fulcrum. When a fulcrum and a bar are used, two different forces exist, the applied force (F_a) and the resultant force (F_r). The forces, bar, and fulcrum can be arranged in three ways, called classes (Fig. 4.1).

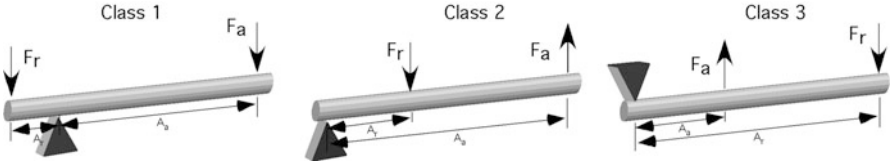


Fig. 4.1 Three classes of levers

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H.L. Field, J.M. Long, *Introduction to Agricultural Engineering Technology*,
https://doi.org/10.1007/978-3-319-69679-9_4

The principle of levers can be expressed mathematically as:

$$\begin{pmatrix}\text{Force}\\ \text{Applied}\end{pmatrix} \times \begin{pmatrix}\text{Arm}\\ \text{Applied}\end{pmatrix} = \begin{pmatrix}\text{Force}\\ \text{Resultant}\end{pmatrix} \times \begin{pmatrix}\text{Arm}\\ \text{Resultant}\end{pmatrix}$$

or

$$F_a \times A_a = F_r \times A_r$$

4.3.1 Class One Lever

In the class one lever, the length of the bar for the applied side of the fulcrum is longer than the length of the bar on the resultant side of the fulcrum (Fig. 4.2). Class one levers are primarily used for their mechanical advantage. The mechanical advantage for a class one lever is the ratio of the lengths of the two arms. For a class one lever, the mechanical advantage is defined as the ratio of the force arm length to the resultant arm length. Expressed mathematically:

$$\text{Mechanical Advantage} = \frac{\text{Force arm length}}{\text{Resultant arm length}}$$

The principles of a class one lever are illustrated by the following problem.

Problem How much weight can a 140.0 pound person lift with a class one lever if the force arm is 4.0 feet long and the resultant arm is 1.0 foot long?

Solution In this problem, three of the variables are known: $F_a = 140$ pounds, $A_a = 4$ feet, and $A_r = 1$ foot (Fig. 4.2). To solve the problem, the lever equation is rearranged to solve for the resultant force.

$$F_a \times A_a = F_r \times A_r$$

$$F_r = \frac{F_a \times A_a}{A_r} = \frac{140.0\ \text{lb} \times 4.0\ \text{ft}}{1.0\ \text{ft}} = 560\ \text{lb}$$

[Note: in this example, two significant digits were used in the answer. This is an example were the significance of the zero in the answer would be ambiguous unless the reader had access to the entire problem. To remove this ambiguity, the answer should be written as 5.5 E2]. With this lever, 140.0 pounds of applied force is

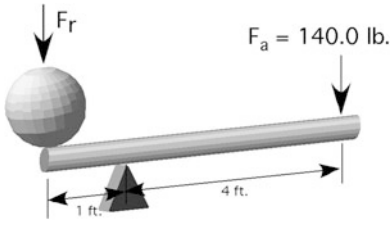

Fig. 4.2 Example of class one lever

capable of lifting 560 pounds. This demonstrates the mechanical advantage of class one levers. The source of the mechanical advantage is clearer if the equation is written as:

$$F_r = \quad 140.0 \text{ lb} \times \frac{4.0 \text{ ft}}{1.0 \text{ ft}}$$

When the equation is arranged in this manner, it is easy to see that the increase in force or mechanical advantage is the ratio of the lengths of the two arms. In this example, the amount of force the person could produce (mechanical advantage) was increased 4/1 or 4 times.

In addition to the mechanical advantage, the relative distance the two ends of the bar will move can also be determined. The distance moved is determined by the ratios of the amount of movement and the lengths arm. For class one lever, the equation is:

$$\frac{\text{Distance moved applied}}{\text{Arm length applied}} = \frac{\text{Distance moved resultant}}{\text{Arm length resulant}} \text{ or } \frac{D_{ma}}{A_{la}} = \frac{D_{mr}}{A_{lr}}$$

Problem Determine the distance the sphere in Fig. 4.2 will move if the bar at the applied end moves 14.0 inches.

Solution The class one lever movement equation is rearranged to solve for the movement of the resultant arm and the appropriate values inserted:

$$\begin{aligned} \frac{D_{ma}}{A_{la}} &= \frac{D_{mr}}{A_{lr}} \\ D_{mr} &= \frac{D_{ma} \times A_{lr}}{A_{la}} \\ &= \frac{(14 \text{ in} \times {}^{1 \text{ ft}}/_{12 \text{ in}}) \quad \times 1 \text{ ft}}{4 \text{ft}} \\ &= 0.29 \text{ ft or } 3.5 \text{ in} \end{aligned}$$

For this problem when the arm at the applied end moves 14 inches, the sphere will move 3.5 inches. The lever has a mechanical advantage for moving the weight, but the applied arm must move a greater distance than the resultant arm.

An example of the use of a class one lever is a wrecking bar pulling a nail (Fig. 4.3).

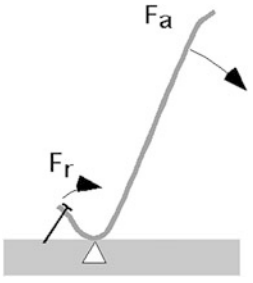

Fig. 4.3 Example of the use of a class one lever

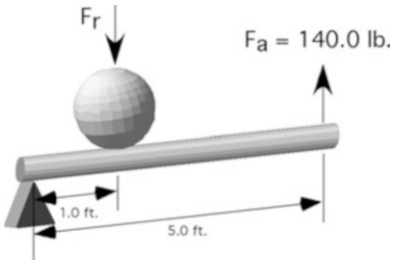

Fig. 4.4 Example of class two lever

4.3.2 Class Two Lever

In class two levers, the resultant force is positioned between the applied force and the fulcrum (Fig. 4.4). The second class of lever also produces a mechanical advantage. In this class of lever, the mechanical advantage is the ratio of the distance between the fulcrum and the applied force and the distance from the fulcrum to the resultant force (Fig. 4.4).

Problem Determine the resultant force for the class two lever in Fig. 4.4.

Solution Use the lever equation. Rearrange the equation to solve for the resultant force. Substitute the appropriate values.

$$F_a \times A_a = F_r \times A^r$$

$$F_r = \frac{F_a \times A_a}{A_r} = \frac{140.0 \text{ lb} \times 5.0 \text{ ft}}{1.0 \text{ ft}} = 700 \text{ lb or } 7.0 \text{ E2 lb}$$

For a class two lever, the mechanical advantage will always be greater than one. In this case, the mechanical advantage is 5 divided by 1 or 5. This is why a 700 pound load can be lifted with only a force of 140 pounds supporting the load at the end of the fulcrum. A common use of a class two lever is the wheelbarrow (Fig. 4.5).

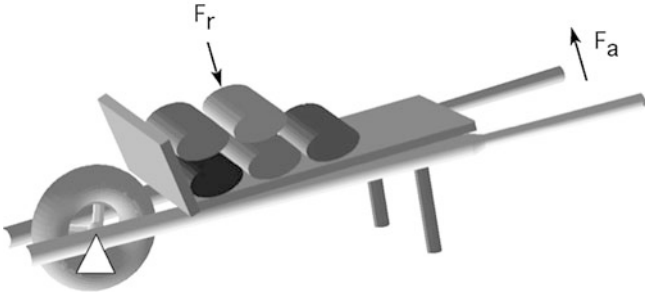

Fig. 4.5 Example of class two lever in use

The movements of class two levers are the same as class one levers. The same equation can be used.

Problem Determine the distance the sphere will move in Fig. 4.4 when the applied force end of the bar is moved 16 inches.

Solution

$$D_{mr} = \frac{D_{ma} \times A_{lr}}{A_{la}}$$
$$= \frac{(16 \text{ in} \times 1 \text{ ft}/12 \text{ in}) \times 1 \text{ ft}}{5 \text{ ft}}$$
$$= 0.2666\ldots \text{ ft or } 3.2 \text{ in}$$

It is important to remember that the determination of the class of lever is based on the location of the fulcrum, the length of the applied force, and the length of the resultant force. If the relationship of these three components changes, the class of lever will change. A two-wheeled dolly can act as a class one or class two lever depending on the position of the load. In Fig. 4.6, the center of the mass on the dolly is to the right of the fulcrum (axle). In this arrangement, the dolly acts as a class one lever.

When the center of mass moves to the left of the fulcrum (axle), the dolly will behave as a class two lever (Fig. 4.7).

In Fig. 4.7, the center of the mass on the dolly has moved to the left of the fulcrum. Also note that the balancing force has changed. It is lifting up on the handle. When used as a class one lever, the operator must provide a constant pull on the handles. When used as a class two lever, the operator must lift up on the handles.

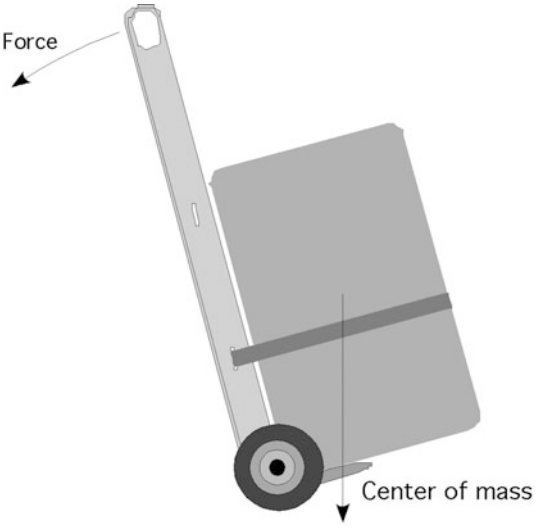

Fig. 4.6 A two-wheeled dolly as a class one lever

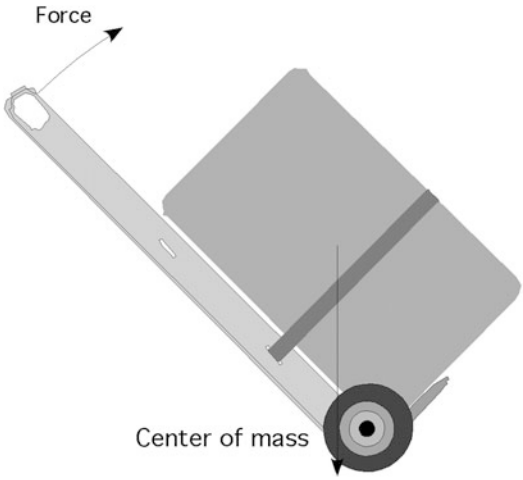

Fig. 4.7 A two-wheeled dolly as a class two lever

4.3.3 Class Three Lever

In class three levers, the applied force is positioned between the resultant force and the fulcrum. The class three lever does not have a mechanical advantage. It is primarily used to increase movement. The same applied force and distances are used to illustrate a class three lever (Fig. 4.8).

Problem Determine the resultant force for the class three lever in Fig. 4.8.

Solution Rearrange the lever equation to solve for the resultant force. Insert the appropriate values:

$$F_a \times A_a = F_r \times A_r$$

$$F_r = \frac{F_a \times A_a}{A_r} = \frac{140.0\ \text{lb} \times 1.0\ \text{ft}}{5.0\ \text{ft}} = 28\ \text{lb}$$

The class three lever will produce a resultant force of 28 pounds.

As this example illustrates, the mechanical advantage for the third class lever will always be less than one. In the example of a class three lever, 140 pounds of

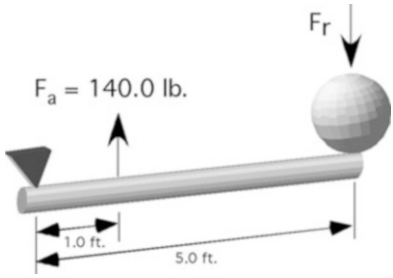

Fig. 4.8 Example of class three lever

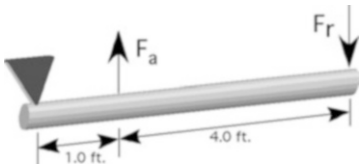

Fig. 4.9 Class three lever with split measurement of length

applied force can only lift a weight of 28 pounds. The distance moved and the speed of movement of the resultant point compared to the applied point are increased proportionally.

It is important to remember in all three classes of levers that the applied length and resultant length are measured from the point of application to the fulcrum. This is important to remember because class two and three levers can be drawn as Fig. 4.9.

In Fig. 4.9, the length of the resultant arm is 5 feet not 4 feet because the distance is measured from the point the force is applied to the fulcrum.

A common use of the class three lever is the three point hitch on a tractor (Fig. 4.10).

The ratio equation is modified for class three levers.

$$D_{\mathrm{r}} = D_{\mathrm{a}} \times \frac{A_{\mathrm{a}}}{A_{\mathrm{r}}}$$

Problem Calculate the movement for the resultant arm for Fig. 4.8.

Solution Rearrange the movement equation to solve for the resultant movement. Insert the appropriate values:

$$\begin{aligned} D_{\mathrm{mr}} &= \frac{D_{\mathrm{ma}} \times A_{\mathrm{lr}}}{A_{\mathrm{la}}} \\ &= \frac{(8\ \mathrm{in} \times 1\ \mathrm{ft}/12\ \mathrm{in}) \times 5\ \mathrm{ft}}{1\ \mathrm{ft}} \\ &= 3.3333 \ldots \mathrm{ft\ or\ 40\ in} \end{aligned}$$

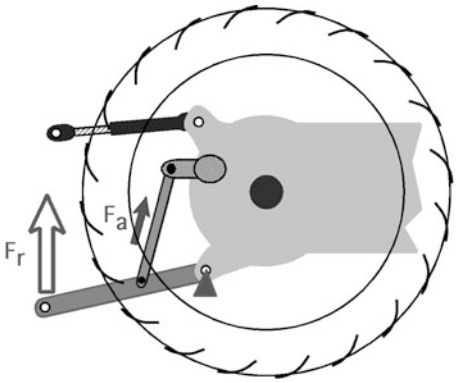

Fig. 4.10 Example of the use of class three lever

4.3.4 Wheel and Axle

A wheel and axle behaves as a continuous lever. The center of the axle corresponds to the fulcrum. A wheel and axle has a mechanical advantage if the radius of the wheel is the applied arm and the radius of the axle is the resultant arm.

When the radius of the wheel is the applied arm, the movement of a line wrapped around the axle will be less than the movement of a line wrapped around the wheel.

The wheel and axle does not have a mechanical advantage when the wheel radius is the resultant arm and the axle radius is the applied arm (Fig. 4.11).

In this arrangement, a line wrapped around the wheel will have more movement than a line wrapped around the axle.

The equation for determining the forces for a wheel and axle is the same as the equation used for the three classes of levers.

$$F_a \times A_a = F_r \times A_r$$

Problem How much force will it take to lift a 10.0 pound weight with a wheel and axle, used as in Fig. 4.11, when the axle is 2.0 inches in diameter and the wheel is 10.0 inches in diameter?

Solution The first step is to rearrange the equation to solve for the applied force. Next, insert the appropriate values. Remember that the length of the force arm is the radius of the wheel and the length of the resultant arm is the radius of the axle.

$$F_a \times A_a = F_r \times A_r$$

$$F_a = \frac{F_r \times A_r}{A_a} = \frac{10.0 \text{ lb} \times 5.0 \text{ in}}{2.0 \text{ in}} = 25.0 \text{ lb}$$

In this example, it will take 25.0 pounds of force on the axle to lift 10 pounds at the wheel.

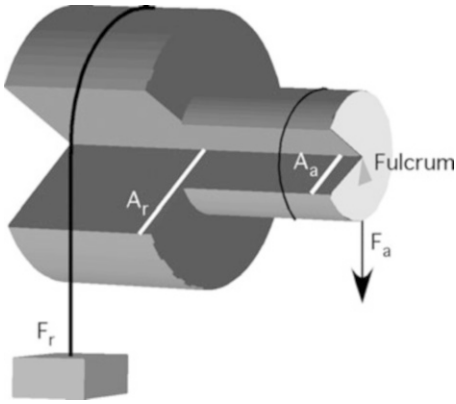

Fig. 4.11 Illustration of wheel and axle with no mechanical advantage

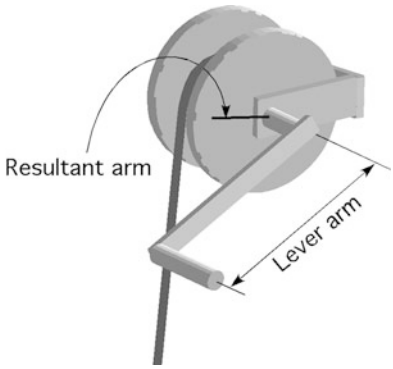

Fig. 4.12 Wheel and axle used as a winch without a gear reducer

Problem Determine the amount of force that would be required to lift a 10.0 pound weight using a wheel with a 10.0 inch diameter and an axle of 2.0 inches when the resultant force is attached to the axle.

Solution

$$F_a \times A_a = F_r \times A_r$$

$$F_a = \frac{F_r \times A_r}{A_a} = \frac{10.0 \text{ lb} \times 2.0 \text{ in}}{5.0 \text{ in}} = 4.0 \text{ lb}$$

In this problem, switching the applied force to the wheel resulted in a reduction in the required amount of force required to lift the weight.

A wheel and axle is not normally used as a single unit. They are usually used in conjunction with a gear reduction system to form a hand or electric motor winch found on boat trailers and other applications.

Problem Determine the amount of pull that will be produced on the cable in Fig. 4.12 if the lever arm is 10 inches long and the wheel diameter is 2.0 inches and a force of 25.0 pounds is applied on the handle.

Solution

$$F_a \times A_a = F_r \times A_r$$

$$F_r = \frac{F_a \times A_a}{A_r} = \frac{25.0 \text{ lb} \times 10.0 \text{ in}}{2.0 \text{ in}} = 125.0 \text{ lb}$$

With 10.0 pounds of force applied to the handle, the winch will produce a pull of 125 pounds on the cable.

4.3.5 Pulley

A pulley is a modification of a first or second class lever. A single pulley does not produce any mechanical advantage; it just changes the direction of force (Fig. 4.13).

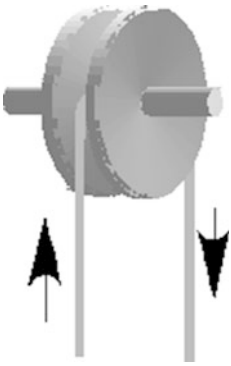

Fig. 4.13 A single pulley

If the power loss to friction is not ignored, then a single pulley has a mechanical advantage of less than one. When pulleys are combined in pairs, a mechanical advantage is produced. This use of pulleys is commonly called a block and tackle.

The amount of mechanical advantage produced by a block and tackle is proportional to the number of ropes that support the weight. The block and tackle in Fig. 4.14 has four ropes, but only three, R_B, R_C, and R_D, support the ball. In this

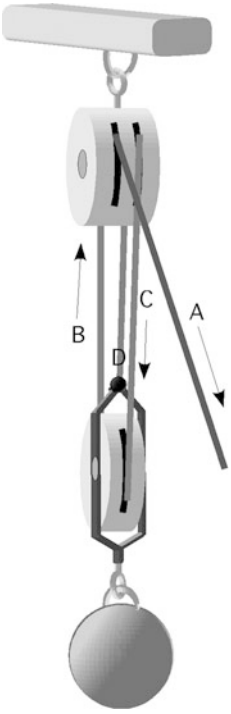

Fig. 4.14 Block and tackle

arrangement, the amount of weight lifted is three times the amount of force being applied. Expressed mathematically:

$$R_n = \frac{W}{F}$$

where W = amount of weight to be lifted; F = amount of force applied to the block and tackle; R_n = number of ropes.

Problem How much pull (pounds of force) is required for the block and tackle in Fig. 4.14 to lift the 545 pound ball?

Solution Study Fig. 4.14 and determine the number of ropes supporting the ball. There are three B, C, and D. The required pull is found by rearranging the pulley equation to solve for F:

$$F = \frac{W}{R_n} = \frac{545 \text{ lb.}}{3} = 181.666 \ldots \text{ or } 182 \text{ lb.}$$

With a three rope block and tackle, 182 pounds of force will lift a 545 pound load, but the haul rope, A, will move three times the distance the load moves.

4.3.6 Inclined Plane

An inclined plane is a flat surface sloping at any angle between vertical and horizontal. An inclined plane produces a mechanical advantage. The amount is determined by the ratio of the inclined plane length to the change in elevation. Instead of lifting the entire weight vertically, part of the weight is supported by the inclined plane.

Figure 4.15 presents two incline planes, AC, that are the same length, just different angles. Intuitive reasoning suggests that if the weight and the distance AC are the same in both cases, less force (ignoring friction) will be required to move the wagon up the inclined plane in drawing I because the change in height is less in I than it is in II. Notice that the incline planes have four variables; they are the length of the incline plane, the change in height of the incline plane, the weight being moved, and the force required to move the weight. An equation has been developed to solve for any one of the variables, when the other three are known.

$$F \times AC = W \times BC$$

where F = amount of force to move the weight (ignoring friction); AC = length of the inclined plane; W = weight; BC = height of the inclined plane.

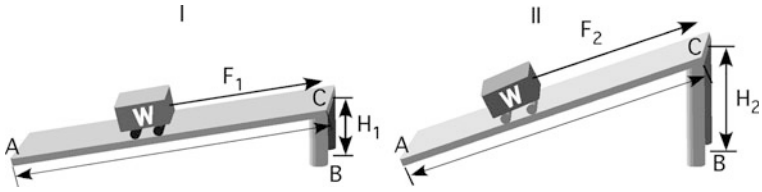

Fig. 4.15 Two incline planes

Problem Determine the amount of force required to move a 100.0 pound weight when the change in height is 2.0 feet and the length of the inclined plane is 12.0 feet.

Solution Rearrange the incline plane equation to solve for force:

$$F = \frac{W \times BC}{AC}$$

Substitute the values:

$$F = \frac{100.0 \text{ lb} \times 2.0 \text{ ft}}{12.0 \text{ ft}} = 16.666 \ldots \text{ or } 17 \text{ lb}$$

The first incline plane in Fig. 4.15 will require 17 pounds of force to move the weight. Remember this assumes no friction.

To illustrate the effect of changing the angle of the inclined plane, the same math will be used for the second inclined plane in Fig. 4.15.

Problem Determine the amount of force required to move the 100.0 pound weight for the second inclined plane when the change in height is 4.0 feet and the length of the incline plane is 12.0 feet.

Solution

$$F = \frac{100.0 \text{ lb.} \times 4.0 \text{ ft.}}{12.0 \text{ ft.}} = 33.33 \ldots \text{ or } 33 \text{ lb.}$$

Comparing the results of these two problems shows that increasing the angle of the incline plane increases the amount of force to move the weight up the plane.

4.3.7 Screw

The screw is a modification of the inclined plane combined with a lever. The threads of a screw or a bolt are an inclined plane that has been rolled into the shape of a cylinder. A lever is used to turn the threads, which causes the load to move along the cylinder. An example of this principle is the screw-type jack (Fig. 4.16). The jack handle is the force arm. The same principle applies to a bolt and nut. In the case of a bolt and nut, the lever arm is the wrench, and the resultant force is the clamping pressure.

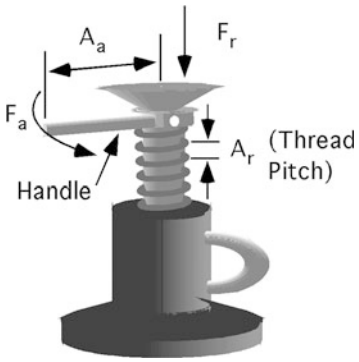

Fig. 4.16 Lever equation applied to a screw

For single lead threads the distance between any two threads, called pitch, determines the amount of movement per revolution. The mechanical advantage is determined by the ratio of the radius of the lever and the pitch distance. The lever equation can be used to express this relationship mathematically:

$$F_a \times A_a = F_r \times A_r$$

where F_a = forced applied at the end of the lever arm; F_r = amount of weight the jack will lift; A_f = length of the lever arm; A_r = pitch of the threads.

Problem A screw jack such as Fig. 4.16 has a 18.0 inch handle and a 0.125 inch thread pitch. How much weight will the jack lift when 50.0 pounds of force is applied at the end of the handle (ignoring friction)?

Solution Rearranging the equation to solve for F_r gives:

$$F_r = \frac{F_a \times A_a}{A_r} = \frac{50.0 \text{ lb} \times 18.0 \text{ in}}{0.125 \text{ in}} = 7200 \text{ lb or } 7.20 \text{ E3 lb}$$

This problem illustrates that a screw jack will lift a large load with a small amount of force. The disadvantage is that the load will only be lifted 0.125 or 1/8 inch for every revolution of the handle.

Friction will affect the performance of this machine more than the others. With the proper lubrication, it can be kept to a manageable level.

4.3.8 Combining Machines

All agricultural machines are a combination of these five simple machines. The analysis of the forces on a machine as complex as a combine exceeds the objectives of this text, but Fig. 4.17 is an example of how two or more of these machines can be used together.

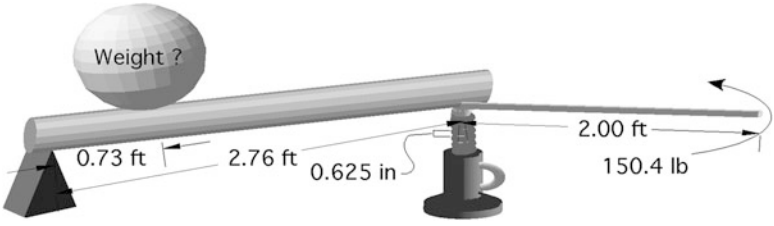

Fig. 4.17 Two machines working in combination

This example is also useful for discussing the problem-solving process. The first inclination is to try and solve for the amount of weight first. If this approach is used, it will soon become evident that an important piece of data is missing. What is the value for the applied force to the lever? The first step is determining the amount of force produced by the jack:

$$F_a \times A_a = F_r \times A_r$$

$$F_r = \frac{F_a \times A_a}{A_r} = \frac{150.4 \text{ lb} \times 2.00 \text{ ft}}{0.625 \text{ in} \times \dfrac{1 \text{ ft}}{12 \text{ in}}} = \frac{300.8}{0.052\ldots} = 5775.36 \text{ lb}$$

[Note: in this example, the answer was not rounded to the appropriate number of significant figures because it is just the first step in a multiple step problem.]

Ignoring friction and the strength of the materials, the jack will be able to produce 5775.36 pounds of force. The force produced by the jack is the applied force for the lever. The amount of weight that can be lifted by the lever is determined by:

$$F_a \times A_a = F_r \times A_r$$

$$F_r = \frac{F_a \times A_a}{A_r} = \frac{5775.36 \text{ lb x } 2.76 \text{ ft}}{0.73 \text{ ft}} = \frac{15939.9936}{0.73} = 21835.607\ldots$$

$$\text{or } 22{,}000 \text{ lb}$$

The machines in the illustration are capable of lifting 22,000 pounds with an application of 150.4 pounds on the jack handle.

4.3.9 Metric Problems

All of the problems in this chapter can be solved using metric units. This will be demonstrated using a class three lever.

Problem Determine the amount of force that will be required by the lift arm to lift the bale of hay in Fig. 4.18. The bale of hay has a mass of 840 kg. The lift arm is

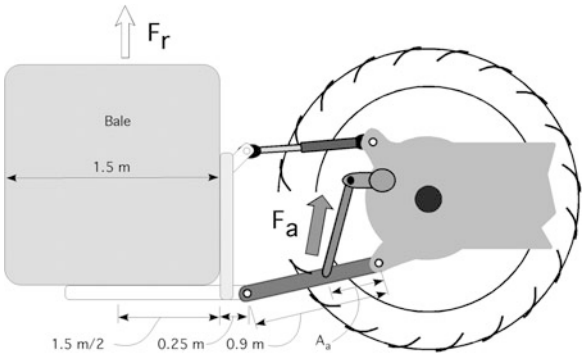

Fig. 4.18 Illustration of bale problem

attached to the lower arm of the hitch 0.5 m from the pivot point, and the length of the lower hitch arm is 0.9 m.

Solution The first step is to convert the weight of the bale. This is accomplished by multiplying the mass of the bale by the acceleration due to gravity:

$$\begin{aligned}\text{Weight } (W) &= \text{mass } (m) \times \text{gravity } (g)\\ &= 840 \text{ kg} \times 9.81 \frac{\text{m}}{\text{s}^2}\\ &= 8240.4 \frac{\text{kg} \bullet \text{m}}{\text{s}^2} \text{ or } 8240.4 \text{ N}\end{aligned}$$

The second step is to calculate the required force using the equation for a class 3 lever. The equation for a class 3 lever is written in terms of a force, but because it is a common practice to use the term weight when referring to the mass of an object, $F_r = W$. This is an example where a serious error can occur because the actual length of the resultant arm is not the length of the lower hitch arm but the distance from the pivot point to the center of the mass of the bale (Fig. 4.18).

Assuming a 1.5 m bale and an additional distance of 25.0 cm from the end of the lower lift arm to the front edge of the bale, the length of the resultant arm is:

$$m = \frac{1.5 \text{ m}}{2} + 0.25 \text{ m} + 0.9 \text{ m} = 1.9 \text{ m}$$

The lift arm force required is:

$$F_a = W \times \frac{A_r}{A_a} = 8240.4 \text{ N} \times \frac{1.9 \text{ m}}{0.50 \text{ m}} = 31313.9 \text{ or } 3.1 \text{ E4 N}$$

The 840 kg bale will require the lift arms on the 3-point hitch to produce 3.1 E4 N of force to lift the bale.

The same procedure can be used to solve any of the other problems in this chapter.

Chapter 5
Internal Combustion Engines

5.1 Objectives

1. Be able to list and describe the events that occur in an internal combustion engine
2. Be able to describe how a spark–ignition (Otto cycle) engine differs in operation from a compression–ignition (diesel cycle) engine
3. Be able to diagram and describe the events that occur in sequence during each stroke of a four-stroke cycle engine
4. Be able to diagram and describe the events that occur in a two-stroke cycle engine
5. Given the bore, stroke, number of cylinders, and clearance volume, be able to calculate the piston displacement, engine displacement, and compression ratio in both customary and SI units

5.2 Introduction

Agriculture uses six sources of power: human labor, domestic animals, wind, flowing water, electricity, and heat engines. Of these, internal combustion engines and electric motors provide the majority of the power, but this is changing. Environmental concerns, government policies, and declining resources are pushing agriculture to adopt alternative sources of energy. Someday fuel cells, solar energy, biomass, and other forms of alternative energy may supply the power for agriculture. For the immediate future, the primary sources of power for agriculture will continue to be internal combustion heat engines and electric motors.

The size of agricultural internal combustion engines range from fractional horsepower hand tools to the hundreds of horsepower required for large tractors. Knowledge of how and why internal combustion engines work is essential to a successful agricultural manager. In this chapter, the basic engine types and functions are discussed, as are some basic calculations concerning engine size (displacement) and compression ratio.

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5.3 Theory of Operation

All internal combustion engines convert the energy of fuel (chemical energy) to power (mechanical energy). They are called internal combustion because burning a fuel in a closed chamber causes an increase in temperature, which causes an increase in pressure. The pressure produces a force on the head of the piston forcing it away from the cylinder head. The linear movement of the piston is converted to rotary motion by the connecting rod and crankshaft Fig. 5.1. The linear movement of the piston is converted because rotary motion is more useful.

All internal combustion engines have eight requirements for operation:

1. Air (oxygen) is drawn into the engine cylinder.
2. A quantity of fuel is introduced into the engine.
3. The air and the fuel are mixed.
4. The fuel–air mixture is compressed.
5. The fuel–air mixture is ignited by the spark plug in gasoline engines or by the heat of compression in diesel engines.
6. The burning of the fuel–air mixture causes a rapid rise in temperature which causes a rapid rise in pressure, which acts against the piston, producing a force on the piston.
7. The use of a connecting rod and a crankshaft converts the linear movement of the piston to rotary motion. The force on the piston is converted to torque on the crankshaft.
8. The products of combustion are expelled from the engine.

The differences between gasoline, liquefied petroleum gas (LPG), and diesel engines are the components and systems they use to complete these eight requirements. The next sections illustrate two ways in which these events occur for four-stroke cycle and two-stroke cycle gasoline and LPG engines.

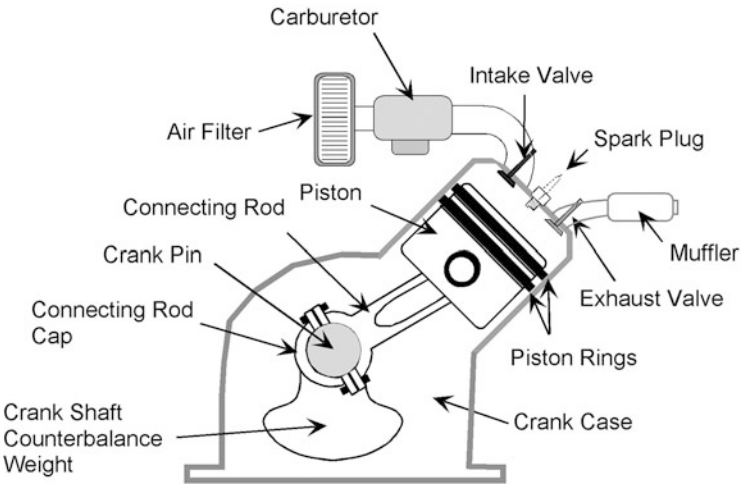

Fig. 5.1 Parts of an internal combustion gasoline engine

5.4 Four-Stroke Cycle

The four-stroke cycle engine, commonly called four-cycle engine, is one of the two common types of engine cycles used for both spark– and compression–ignition (diesel) engines. In four-cycle engines, the eight requirements occur during four strokes of the piston or two revolutions of the crankshaft. The four strokes are called:

1. Intake
2. Compression
3. Power
4. Exhaust

Figure 5.2 illustrates the four strokes. The cycle will be explained starting with the intake stroke.

5.4.1 Intake Stroke

During the intake stroke, the piston travels from the top of the cylinder (TDC) to the bottom of the cylinder (BDC). At the beginning of the cycle, the intake valve opens. As the piston moves downward, the volume in the cylinder between the piston and the cylinder head, or combustion chamber volume, increases. Increasing the volume of the combustion chamber reduces the pressure. Once the pressure drops below atmospheric pressure, air flows through the open intake system and into the combustion chamber. In carbureted engines the air flows through the carburetor as it flows into the combustion chamber, and fuel is introduced into the air stream as it flows through the carburetor. Engines using fuel injection wait and inject the fuel at the end of the stroke. As the piston reaches the BDC on the intake stroke, the intake valve closes, trapping the fuel–air mixture inside the cylinder.

This process is critical for engine power and efficiency. Any restrictions in the flow of air into the engine reduce its volumetric efficiency. Volumetric efficiency is the comparison of how much air flows into the cylinder compared to the amount of air the cylinder can hold when it is totally full at atmospheric pressure. Reducing volumetric efficiency reduces the power produced.

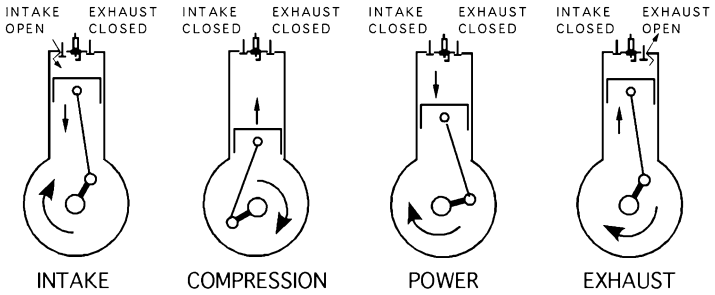

Fig. 5.2 The four strokes of the four-stroke cycle

5.4.2 Compression Stroke

The compression stroke follows the intake stroke. During the compression stroke, both valves are closed and the piston moves from BDC to TDC. This movement of the piston reduces the volume of the combustion chamber from the maximum to the minimum. Reducing the volume through compression increases the pressure and the temperature. As the piston nears the top of the compression stroke, ignition occurs.

For best engine performance, the pressure in the cylinder must be contained in the combustion chamber. If any of the pressure escapes from the combustion chamber, less power will be produced. On engines with excessive hours and/or poor maintenance, the rings become less capable of sealing the space between the piston and the cylinder walls. When this occurs some of the compressed gases blow by the rings and into the crankcase. Another potential source of loss are the valves. They seal utilizing metal to metal contact, which can fail with use and abuse.

5.4.3 Power Stroke

The third stroke is called the power stroke. During the power stroke, the chemical energy of the fuel is converted to power. In the power stroke, both valves are closed and the piston moves from TDC to BDC. Pressure is the key for converting the energy of the fuel to power. Compressing the fuel–air mixture before combustion increases the pressure after combustion and also increases the temperature in the combustion chamber, which helps vaporize the fuel. During the power stroke, the rise in temperature causes a rise in pressure. Increased pressure results in increased force on the piston.

$$F\ (\text{lb}) = P\left(\frac{\text{lb}}{\text{in}^2}\right) \times A\ \left(\text{in}^2\right)$$

Increased force on the piston produces more torque on the crankshaft. Increased torque means increased power.

As the piston approaches the bottom of the stroke, the exhaust valves open, which starts the process of removing the exhaust gases from the engine. As the piston returns toward the top of the cylinder, on the next stroke, the remaining by-products of combustion are expelled from the cylinder through the open exhaust valve. This is called the exhaust stroke.

5.4.4 Exhaust Stroke

The exhaust stroke follows the power stroke. At the beginning of the stroke, the exhaust valve is open and the intake valve is closed. The piston moves from BDC to TDC. During the movement of the piston, the exhaust gases are expelled from the engine. As the piston reaches TDC on the exhaust stroke the intake valves open and the cycle repeats. Four strokes of the piston and two revolutions of the crankshaft have been completed.

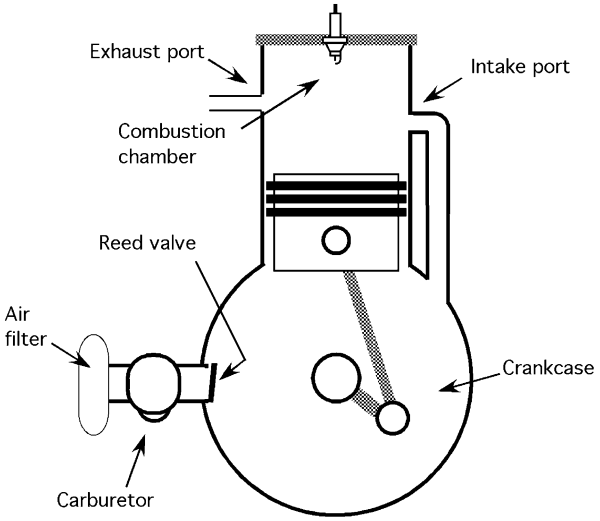

Fig. 5.3 Parts of a two-stroke cycle engine

5.5 Two-Stroke Cycle

In a two-stroke cycle engine, commonly called the two-cycle engine, the eight events occur during two strokes of the piston, one revolution of the crankshaft. Many variations of two-stroke engines are produced. The following sections will explain the operation of the common two-cycle design for gasoline powered engines.

Two very noticeable differences exist between two-cycle and four-cycle engines. In two-cycle engines, the carburetor is attached to the crankcase, and the engine does not have intake or exhaust valves. Attaching the carburetor to the crankcase is the reason oil is mixed with the gas for two-cycle engines. It is the means for lubricating the internal parts.

Ports are used instead of valves to provide a means to get gases into and out of the combustion chamber. Ports are holes in the cylinder wall that are exposed and covered by the movement of the piston (Fig. 5.3).

Study Fig. 5.4 and the following description of events to understand the operation of a two-cycle engine. The description of the cycle starts after combustion.

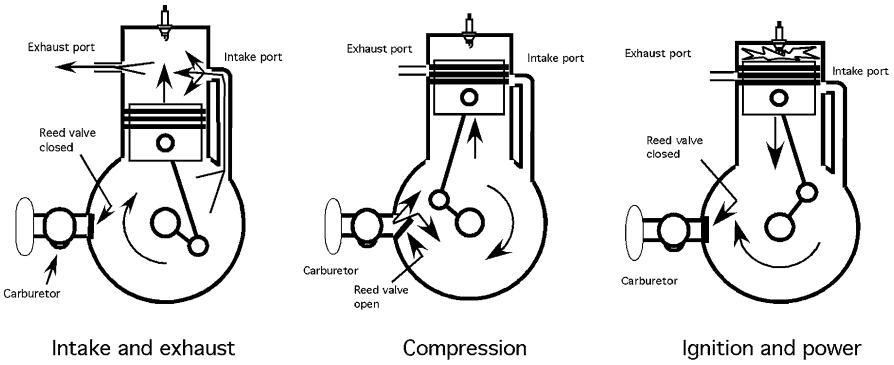

Fig. 5.4 Two-stroke cycle

5.5.1 *Intake–Exhaust Stroke*

In a two-cycle engine, intake and exhaust occur on the same stroke. At the start of the intake–exhaust stroke, the piston is at TDC, and the reed valve is closed. With the reed valve closed, the movement of the piston also starts compressing the air–fuel–oil mixture in the crankcase. After the piston moves away from the cylinder head at a short distance, it exposes the exhaust port. When the exhaust port is exposed, the gases in the combustion chamber start to flow out the exhaust port. As the piston continues to travel toward BDC, it continues to compress the air–fuel–oil mixture in the crankcase and exposes the intake port. When the intake port is exposed, the pressurized air–fuel–oil mixture in the crankcase flows into the cylinder. This flow delivers the next air–fuel–oil charge for combustion and helps expel the exhaust gases.

5.5.2 *Compression Stroke*

During the compression stroke, the piston moves from BDC to TDC. As the piston moves toward TDC, it closes the intake port first, and then it closes the exhaust port. As soon as the intake port is covered, the continuing movement of the piston toward TDC lowers the pressure in the crankcase. The reed valve opens, and the air–fuel–oil mixture flows through the carburetor, through the reed valve and into the crankcase. As soon as the exhaust port is closed, the movement of the piston toward TDC compresses the air–fuel–oil mixture.

As the piston approaches TDC, the spark plug fires, combustion occurs, and pressure builds rapidly in the cylinder. This is called the ignition and power event. As soon as the piston moves away from the head far enough to expose the exhaust port, the cycle begins again.

The eight events occur in two strokes of the piston, one revolution of the crankshaft. A two-cycle engine will produce less power per stroke than a four-cycle engine because both the exhaust and the intake processes are not as efficient. However, because it has a power event in each crankshaft revolution, the total power produced by the engine is comparable to that of a four-cycle engine.

5.6 Types of Engines

The two major categories of internal combustion engines are the spark–ignition (Otto cycle) and the compression–ignition (diesel cycle). In the spark–ignition engine, the fuel is metered and introduced into the engine by either a carburetor or an injection system (Fig. 5.5). When a carburetor is used, the fuel is metered by jets and orifices in the carburetor and added to the air as it flows through the venturi of the carburetor. The fuel is atomized and vaporized as it moves through the intake system and into the cylinder. A spark plug ignites the fuel–air mixture at the proper time.

Fuel injection systems improve the fuel efficiency of a gasoline engine because multiple sensors and a computer can better match the fuel needs of the engine. Historically the additional cost of the system over a carburetor fuel system has limited its use to multicylinder engines, but rising fuel costs and tighter emission standards have prompted manufacturers to use fuel injection systems on smaller engines.

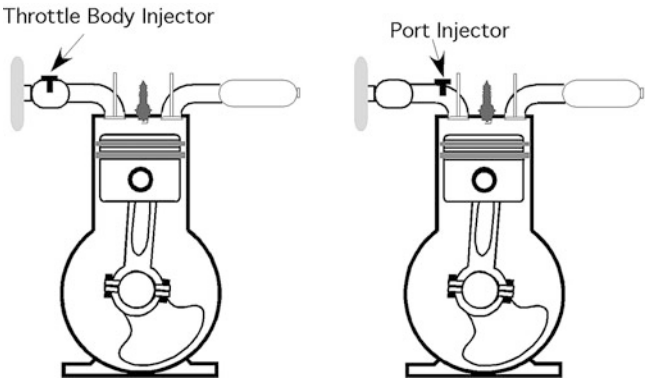

Fig. 5.5 Throttle body and port injection

A fuel-injected engine does not have a carburetor. In early fuel-injected engines, the injector was located in a throttle body mounted in the intake system. One injector could supply the fuel to multiple cylinders. The next generation of fuel injection systems located the injector(s) just outside the intake valve(s). This improved the fuel efficiency of the engines and has been used for many years. The third generation of fuel injection systems is called direct injection. In direct injection engines, the gasoline is injected into the combustion chamber. Direct injection provides the best system for matching the fuel to the engine load and speed.

In a compression–ignition engine (diesel), the fuel is injected directly into the combustion chamber (Fig. 5.6). The injection is timed to occur just before TDC on the compression stroke. Combustion occurs almost instantaneously because compression causes the air temperature within the combustion chamber to rise to 1000 °F and above. Thus, there is no need for a spark plug to ignite the fuel. The injector pump controls the amount of fuel delivered to each cylinder.

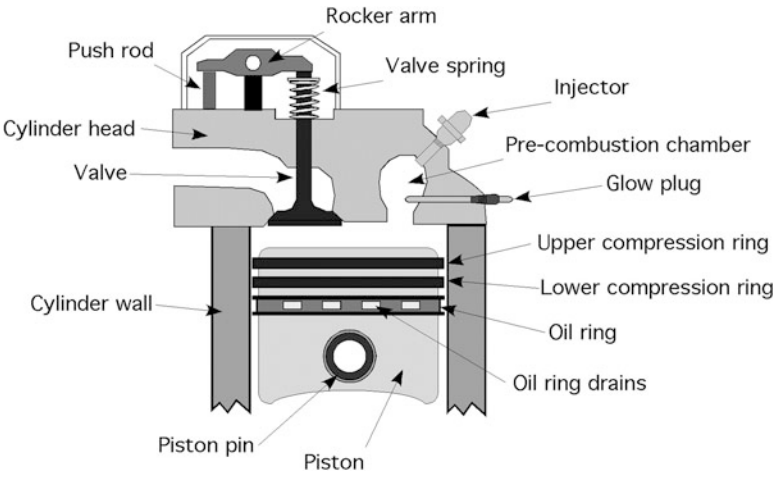

Fig. 5.6 Parts of diesel engine

5.7 Displacement

Displacement is the cylindrical volume that a piston displaces as it moves through one stroke. It is equal to the area of the piston multiplied by the length of the stroke. Displacement is one of the factors that determine the horsepower produced by an engine. The greater the displacement, the greater the volume of air and fuel that is burned during combustion, which means more power. Expressed mathematically, piston displacement is:

$$PD = \frac{\pi \times B^2}{4} \times S$$

where PD = piston displacement in cubic inches (in^3); B = bore of cylinder (diameter), in inches (in); S = stroke of piston in inches (in).

The bore and the stroke of an engine have been traditionally expressed as $B \times S$ with the dimensions in inches. Thus, if $B \times S = 3.50 \times 4.00$, the piston displacement is:

$$PD = \frac{\pi \times B^2}{4} \times S = \frac{\pi \times (3.50\ \text{in})^2}{4} \times 4.00\ \text{in} = 38.484 \ldots \text{or } 38.5\ \text{in}^3$$

Larger engines are constructed with more than one cylinder. For multicylinder engines, the term engine displacement (ED) is used. Engine displacement is the product of the cylinder displacement times the number of cylinders. Expressed in equation form:

$$ED = PD \times n$$

where ED = engine displacement (in^3); PD = piston displacement (in^3); n = number of cylinders.

If the engine in the previous example is a four-cylinder engine, then the engine displacement is:

$$ED = PD \times n = 38.5 \times 4 = 154\ \text{in}^3$$

It is a common practice to combine these two equations. For a single-cylinder engine, the value for $n = 1$:

$$ED = \frac{\pi \times B^2 \times S}{4} \times n$$

5.7.1 Compression Ratio

The compression ratio is the ratio of the total volume in a cylinder to the clearance volume. The clearance volume is the volume of the combustion chamber when the piston is a TDC (Fig. 5.7). The total volume is the clearance volume plus the displacement.

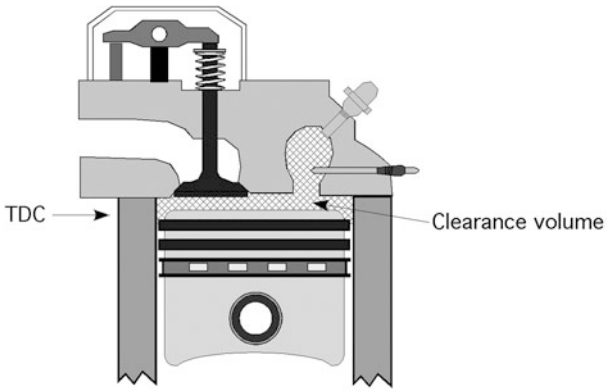

Fig. 5.7 Cylinder clearance volume

The compression ratio is an engine characteristic related to engine efficiency, that is, the ability of the engine to convert energy in the fuel to useful mechanical energy. Increasing the compression ratio increases the efficiency of the engine but changes the fuel requirements. The maximum compression ratio that can be utilized in an engine design is a function of the type of fuel and the physical strength of the engine components. A compression ratio of 7 to 8:1 is common for gasoline engines, and a ratio of 15 to 22:1 is common for diesel engines.

Expressed mathematically compression ratio is:

$$CR = \frac{PD \ + \ CV}{CV}$$

where CR = Compression ratio; PD = Piston displacement (in^3); CV = Clearance volume (in^3).

Problem Determine the compression ratio for a single-cylinder engine with a $B \times S$ of 3.25×3.75 and a clearance volume of 6.20 in^3.

Solution The first step is to calculate the displacement:

$$PD = \frac{\pi \times B^2}{4} \times S \times n = \frac{3.14 \times \ (3.25 \text{ in})^2}{4} \times 3.75 \times 1 = 31.093 \ldots \text{ or } 31.1 \text{ in}^3$$

Then the compression ratio is:

$$CR = \frac{31.1 \text{ in}^3 + 6.2 \text{ in}^3}{6.2 \text{ in}^3} = 6.0 \text{ as a ratio } 6.0 : 1$$

Notice that the answer has no units. To have a ratio, the units in the numerator and the denominator must be the same; thus the units cancel each other. A compression ratio of 6.0 would be expressed as 6.0:1.

5.7.2 Theoretical Power

In the previous chapter, theoretical power was defined as the calculated horsepower based on the bore, cylinder pressure, and engine speed. Figure 5.8 shows a typical cylinder pressure curve for a naturally aspirated engine. During the intake stroke, the pressure is below zero, atmospheric pressure. The pressure increases as the piston moves through the compression stroke and then jumps rapidly at combustion. During the power stroke and exhaust stroke, the cylinder pressure gradually drops back to zero. The average pressure for the complete cycle is used to calculate engine power.

The theoretical or indicated engine horsepower can be determined using the mean effective cylinder pressure (MEP). It does not account for the power lost to friction and other losses. The MEP can be determined from the graph, but these calculations are beyond the math level for this text. The equation for calculating indicated engine power in units of horsepower is:

$$E_{\text{hp}} = \frac{P \times S \times A \times N}{33{,}000 \times Z} \times n$$

where P = Mean effective pressure (psi); S = Stroke (ft); A = Cylinder area (in^2); N = Engine speed (rpm); n = Number of cylinders; $Z = 2$ for four cycle engines; $Z = 1$ for two cycle engines.

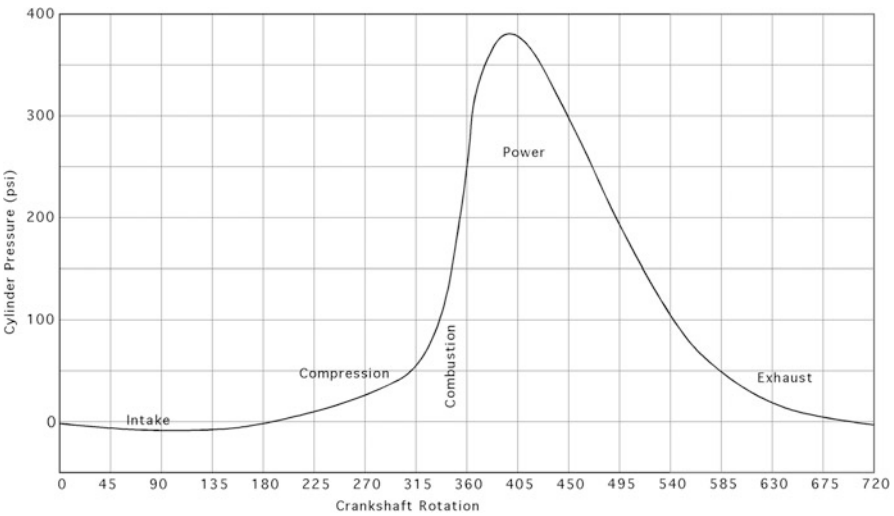

Fig. 5.8 Cylinder pressure example

Problem Determine the indicated horse power for a four-cycle, single-cylinder engine that has a mean effective pressure of 152.0 psi. The bore is 2.75 inches, the stroke is 2.65 inches, and the engine speed is 3000 revolutions per minute.

Solution The engine power for four-cycle engines can be calculated using the following equation:

$$\begin{aligned} E_{\text{hp}} &= \frac{P \times S \times A \times N}{33{,}000 \times Z} \times n \\ &= \frac{152.0 \dfrac{\text{lb}}{\text{in}^2} \times \left(2.65 \text{ in} \times \dfrac{1 \text{ ft}}{12 \text{ in}}\right) \times \left(\pi \times \left(\dfrac{2.75 \text{ in}}{2}\right)^2\right) \times 3000 \text{ rpm}}{33{,}000 \times 2} \times 1 \\ &= \frac{152 \times 0.22083\ldots \times 5.939\ldots \times 3000}{66{,}000} \\ &= \frac{598{,}115.0626}{66{,}000} = 9.0623\ldots \text{ or } 9.06 \text{ Ehp} \end{aligned}$$

5.7.3 Metric Problems

The unit of engine power in the SI system is the kilowatt (kW). Piston bore and stroke are measured in millimeters. Displacement is reported in liters. One liter is equal to 1000 cm^3 or 1,000,000 mm^3. Pressure is measured in pascals (Pa). The equation for engine power in kW is:

$$E_{\text{kW}} = \frac{P \times S \times A \times N}{60{,}000 \times Z} \times n$$

where P = mean effective pressure (P); S = stroke (m); A = cylinder area (m^2); N = engine speed (rpm); n = number of cylinders; $Z = 2$ for four cycle engines; $Z = 1$ for two cycle engines.

Problem Determine the indicated engine power for an engine in units of kW, with a mean effective pressure of 1050 kPa. The engine is a four-stroke engine and has three cylinders. The bore (B) is 109 mm, the stroke (S) is 115 mm, and the speed is 3000 revolutions per minute.

Solution First convert the units to base SI units:

$$P = 1050 \text{ kPa} = 1050 \text{ kPa} \times \frac{1000 \text{ Pa}}{1 \text{ kPa}} = 1{,}050{,}000 \text{ Pa}$$

$$B = 109 \text{ mm} = 109 \text{ mm} \times \frac{1 \text{ m}}{1000 \text{ mm}} = 0.109 \text{ m}$$

$$S = 115 \text{ mm} = 115 \text{ mm} \times \frac{1 \text{ m}}{1000 \text{ mm}} = 0.115 \text{ m}$$

Next calculate the area of the piston:

$$A\ (\mathrm{m}^2) = \pi \times \frac{B^2}{4} = \pi \times \frac{(0.109\ \mathrm{m})^2}{4} = 0.0093313\ldots \text{ or } 0.00933\ \mathrm{m}^2$$

Finally determine the kilowatts:

$$\begin{aligned} E_{\mathrm{kW}} &= \frac{P \times S \times A \times N}{60{,}000 \times Z} \times n \\ &= \frac{1.050\ \text{E6 Pa} \times 0.115\ \mathrm{m} \times 0.009331\ldots \mathrm{m}^2 \times 3000\ \frac{\mathrm{rev}}{\mathrm{min}}}{60{,}000 \times 2} \times 3 \\ &= \frac{3380{,}269.069}{120{,}000} \\ &= 28.168\ldots \text{ or } 28.2\ \mathrm{kW} \end{aligned}$$

Problem Calculate the compression ratio for the engine in the previous problem if the clearance volume is 0.063124 L.

Solution Since ratio does not have units, any consistent set of units can be used. Engine displacement is usually expressed in liters; therefore, in this example the displacement is converted to liters because the clearance volume is in units of liters.

Start by calculating the piston displacement in liters:

$$\begin{aligned} PD\ (\mathrm{L}) &= S \times \pi \times \frac{B^2}{4} \times \frac{1\ \mathrm{L}}{1.0\ \text{E-3 m}^3} \\ &= 0.115\ \mathrm{m} \times 3.1416 \times \frac{(0.109\ \mathrm{m})^2}{4} \times \frac{1\ \mathrm{L}}{1.0\ \text{E-3 m}^3} \\ &= \frac{0.00429240516\ldots}{4.0\ \text{E-3}} \\ &= 1.0731\ldots \text{ or } 1.07\ \mathrm{L} \end{aligned}$$

Next calculate the compression ratio:

$$\begin{aligned} CR &= \frac{PD + CV}{CV} \\ &= \frac{1.07\ \mathrm{L} + 0.063124\ \mathrm{L}}{0.063124\ \mathrm{L}} \\ &= \frac{1.133124}{0.063124} \\ &= 17.950\ldots \text{ or } 18 \text{ to } 1 \end{aligned}$$

Chapter 6
Powertrains

6.1 Objectives

1. Be able to describe mechanical, pneumatic, and hydraulic powertrains
2. Be able to determine the appropriate size for a pulley, sprocket, or gear
3. Be able to use speed ratios to determine pulley, sprocket, and gear sizes
4. Be able to determine the speed and direction of rotation at any point in a powertrain
5. Be able to understand the relationship between speed and torque
6. Be able to determine the torque and power at any point in a powertrain
7. Be able to calculate the movement and changes in force for a hydraulic powertrain

6.2 Introduction

Machines such as push lawn mowers, pumps, and generators utilize the power directly from the engine crankshaft, but many agricultural machines require power at locations away from the engine. In addition, the power demands may require modification such as a different speed or different direction of rotation. The collection of machine components that modify and deliver the power to remote locations from the engine it is called the powertrain or drivetrain. In complex agricultural machines, such as a combine, the power must be delivered to multiple locations and modified several times to meet the needs of the different machine components.

The transportation and modification of power can be accomplished using mechanical, pneumatic, hydraulic, or electrical systems. Mechanical systems are very common on agricultural machines. They are very different components than the other systems so they will be discussed separately. Hydraulic and pneumatic systems have enough similarities that they will be discussed together. Electrical systems will not be included in this section. They are included in a separate chapter. Each of these systems use a different means to modify and deliver power, and each has advantages and disadvantages. The remaining sections of this chapter will

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explain how these power transfer systems work. Note: None of the systems are 100% efficient in the transfer of power, but energy losses will be ignored during the following sections to make it easier to understand how each system functions.

6.3 Mechanical Systems

Mechanical power systems utilize pulleys, sprockets, gears, bearings, shafts, and numerous other components to deliver power to the individual components of a machine and to modify it to meet each component's requirements. The next sections illustrate some of the principles of mechanical powertrains and provide examples of how these principles are used.

6.3.1 Pulleys

Pulleys are used with belts to transmit power. Originally agricultural machines used flat belts and pulleys, but these have been replaced with V-belts. V-belt pulleys or sheaves are used because the belt wedges in the pulley, which increases the friction between the belt and the pulley. Greater friction between the belt and the pulley results in greater potential power transmission. A belt drive will always have at least two pulleys, the driver and the driven. Consider Fig. 6.1, which is a drawing of two pulleys mounted on separate shafts and connected by a belt.

When torque is applied to the driver shaft, it turns or rotates as indicated by the arrow on the driver pulley (Fig. 6.1). The rotation of the driver pulley causes a tension or force on the belt. If the tension or force on the belt exceeds the load (torque) of the driven pulley, the driven pulley will rotate. Drivetrains using belts and pulleys may contain more than two pulleys. If more than two are used, one will be the driver and the others will be driven.

If the driver pulley in Fig. 6.1 has a diameter of 10.0 inches and rotates at 100.0 revolutions per minute (rpm), and the driven pulley has a diameter of 5.0 inches, we can determine the speed of the driven pulley (and the shaft it is attached to) because the diameter of the driver pulley times the speed of the driver pulley is equal to the

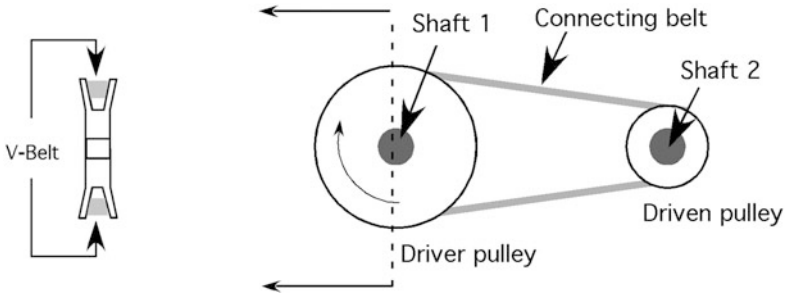


Fig. 6.1 Parts of a V-belt system

diameter of the driven pulley times the speed of the driven pulley. Expressed mathematically the pulley equation is:

$$D_1 \times N_1 = D_2 \times N_2$$

where D_1 = Diameter driver pulley; D_2 = Diameter of driven pulley; N_1 = Driver pulley speed in revolutions per minute; N_2 = Driven pulley speed in revolutions per minute.

This equation is true because the linear speed (feet per minute) of the belt remains constant. If we identify D_1 as the diameter of the driver pulley and D_2 as the diameter of the driven pulley, the speed of the driven pulley can be determined by rearranging the pulley equation:

$$N_2 = \frac{D_1 \times N_1}{D_2} \text{ or } \frac{D_1}{D_2} \times N_1$$

Using the example problem:

$$N_2 = \frac{10.0 \text{ in.} \times 100 \text{ rpm}}{5.0 \text{ in.}} = 200 \text{ rpm}$$

This example demonstrates that when the driven pulley is smaller than the driver, the speed will increase. When the driven pulley is larger than the driver, the speed will decrease. Thus by visual inspection and intuitive reasoning, you should be able to tell if a pulley drivetrain will increase or decrease the speed. To determine the actual amount of change, use the pulley equation.

One application of this principle is represented in the fan drive in Fig. 6.2. Large ventilation fans of this type are commonly used in greenhouses, livestock buildings, and other agricultural applications. These fans have an optimal speed. Electric motors have a standard speed of 1725 revolutions per minute; therefore, the speed of the fan is determined by the diameter ratio of the two pulleys.

Problem Assume that you have a fan and an electric motor but no pulleys, Fig. 6.2. The fan is designed to operate at 500 rpm, and the electric motor operates at 1725 rpm. What sizes of pulleys will be needed to operate the fan?

Solution At this point only two of the four variables in the pulley equation are known. These are the speeds. To find a solution, one of the pulley sizes must be

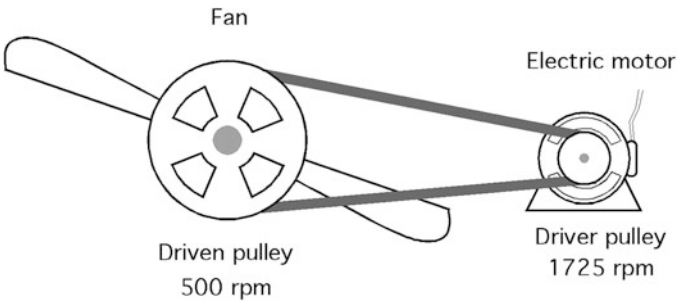


Fig. 6.2 Determining unknown pulley size

selected and the second one calculated. The pulley for the fan could be selected first, but because the fan speed (driven) is less than the motor speed (driver), we know that the pulley on the motor will be smaller than the pulley on the fan. If the pulley selected for the fan is too small, the calculated pulley size for the electric motor may be smaller than what is physically possible. Therefore, begin by selecting the pulley size for the electric motor and then calculate the required pulley size for the fan.

This example starts by selecting a 2.5 inch pulley for the motor. The size of the fan pulley is determined by rearranging the pulley equation:

$$D_2(\text{fan}) = \frac{D_1(\text{motor}) \times N_1}{N_2} = \frac{2.50 \text{ in.} \times 1725 \text{ rpm}}{500 \text{ rpm}} = 8.62 \text{ in.or } 8\frac{5}{8}\text{in.}$$

A fractional size pulley may not be available. If so, a 9- or 8-inch pulley would be used.

This illustrates a principle of problem-solving. The calculations may not produce the desired answer; they may just help make a more informed decision. If the 9-inch pulley is used, the fan would operate at a slightly slower than 500 rpm. If the 8-inch pulley is used, the fan would operate at a slightly faster than 500 rpm.

Note that the ratios of the pulley diameters, D_2/D_1, are equal to the ratios of the pulley speeds, $N_1/N_2 = 3.45$. Thus if the 2.5 inch pulley for the motor is not available, any combination of pulley diameters with a ratio of 3.45 (or $\cong$ 3.5) will provide the desired speed. Pulleys with diameters of 8.625 and 2.5 or 17.25 and 5.0 or 34.5 and 10.0 will produce the same change in speed. This ratio of two pulleys is called the speed ratio, and it will be discussed in more detail later in this chapter.

6.3.2 Sprocket Sizes

Roller chains and sprockets (Fig. 6.3) have two advantages over belts and pulleys. They are capable of transmitting greater amounts of power, and because it is impossible for the chain to slip, the sprockets stay in time.

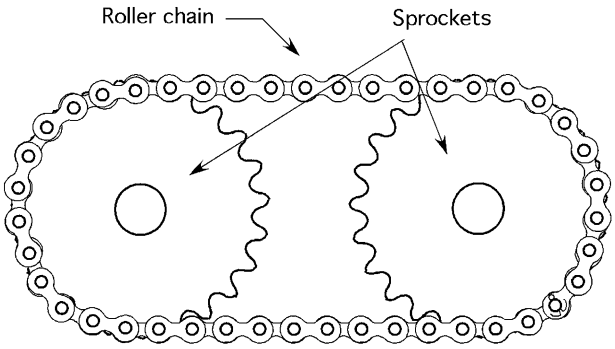


Fig. 6.3 Roller chain and sprockets

The equation used with pulleys can be used to determine sprocket sizes by replacing the diameter of the pulley with the teeth for each sprocket. For sprockets, the pulley equation becomes:

$$T_1 \times N_1 = T_2 \times N_2$$

where T_1 = Number of teeth in driver sprocket; T_2 = Number of teeth in driven sprocket; N_1 = Speed of driver sprocket, rpm; N_2 = Speed of driven sprocket, rpm.

Problem A hydraulic pump is attached to a tractor power take-off (PTO) by a chain and sprockets. The desired speed of the pump is 2100 rpm. The PTO operates at 540 rpm. What sizes of sprockets are needed?

Solution The first step is to select the size of one of the sprockets. In this example, the driven sprocket (pump) will have fewer teeth than the driver sprocket (PTO) because it has a higher rpm. Start by selecting an 18-tooth sprocket for the pump and then determine the size of the PTO sprocket.

Rearranging the sprocket equation for the number of teeth in the driver sprocket:

$$T_1 = \frac{T_2 \times N_2}{N_1} = \frac{18 \text{ teeth} \times 2100 \text{ rpm}}{540 \text{ rpm}} = 70 \text{ teeth}$$

The pump will turn at the correct speed if the PTO sprocket of the tractor has 70 teeth.

6.3.3 Gear Sizes

It is common to use gears in powertrains when the shafts are very close together, when a large amount of power is being transmitted or in transmissions where selectable speed ratios are needed. The sizes of gears are determined in the same way as those of chains and sprockets. The sprocket equation can be used without modification.

6.3.4 Speed Ratios

In some situations when the speeds of the driver and driven shafts are known, pulley, sprocket, and gear sizes can be determined by using speed ratios instead of the pulley or sprocket equations.

In the previous problem, a 70-tooth sprocket was needed to power the pump. A 70-tooth sprocket will have a large diameter and may be too large to fit on a small tractor. Does this mean that the pump cannot be used?

The solution is to use a smaller sprocket on the pump and then determine the size of sprocket needed for the PTO. In the original problem, we saw that 18- and 70-tooth sprockets would provide the correct speed. Thus we know that the ratio of the two sprockets is 70/18 or 3.9:1. In other words, the sprocket on the PTO must have approximately four times as many teeth as the sprocket on the pump.

With the speed ratio between the two shafts known, several different sprocket combinations could be used:

$$\frac{T_1}{T_2} = \frac{70}{18} \text{ or } \frac{35}{9} \text{ or } \frac{43}{11} = 3.9$$

In these situations, the ratio does not usually need to be exact for the system to operate. A hydraulic pump that runs slightly faster or slower, because the exact speed ratio cannot be used, usually performs adequately. Knowing the speed ratio makes it easier to select sprocket combinations that will operate the pump at the correct speed and still fit within the physical limitations of the machine.

6.3.5 Direction of Rotation

The previous section explained using powertrains to change the speed between two or more shafts and components. Another function of mechanical powertrains is changing the direction of rotation. In many applications, a shaft or component may need to turn in the opposite direction as the driver. The two directions of rotation are labeled clockwise (CW) and counterclockwise (CCW) when viewed from the end of the shaft. The direction of rotation can be changed through the use of belts and pulleys, chains and sprockets, and gears. Each of these methods will be illustrated.

6.3.5.1 Belts and Pulleys

Two different techniques can be used to change the direction of rotation using belts and pulleys (Fig. 6.4).

Twisting the belt changes the direction of rotation, but for this technique to provide acceptable results, the pulleys must be some distance apart, the belt must operate at slow speed, and the belt must not be transmitting a large load. The belts will rub where they cross producing friction. These three restrictions should keep the friction at an acceptable level. Even so, the friction produced from rubbing will shorten the life of the belt.

The addition of another pulley will reverse the direction of rotation for the third pulley (Fig. 6.4). If the third pulley has a large load, the system must be modified. A six-sided, or double-V, belt could be used or the system can be designed with a double-cogged belt. If it is transmitting a small load, a flat pulley can be used.

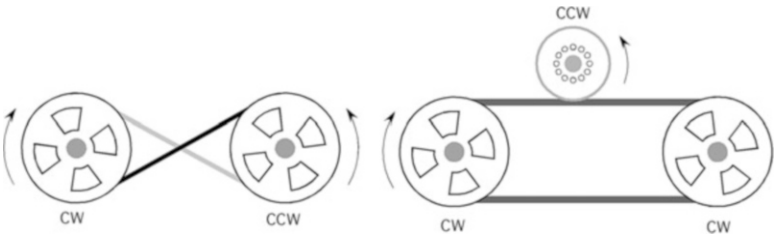


Fig. 6.4 Changing the direction of rotation using belts

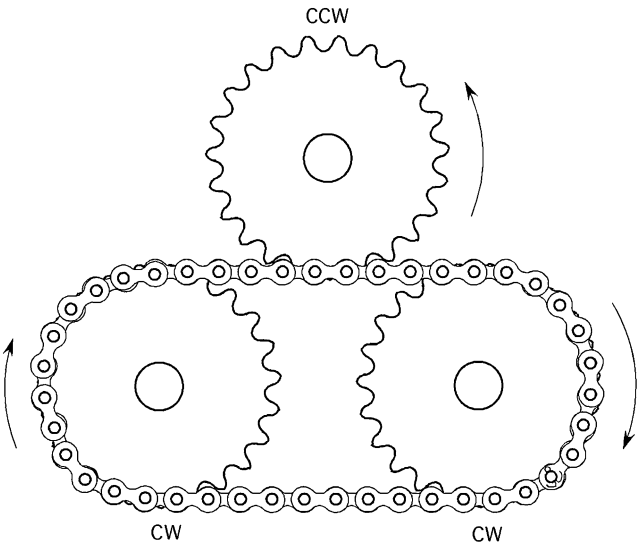


Fig. 6.5 Changing the direction of rotation with a roller chain and sprockets

The use of a third pulley also provides an opportunity to change the speed of rotation. Any difference in diameter between the third pulley and the driver pulley will cause a change in the speed of the third pulley.

6.3.5.2 Roller Chains and Sprockets

Figure 6.5 shows that chains and sprockets can also be used to reverse the direction of rotation. Because roller chains cannot be twisted, changing the direction of rotation requires the use of an additional sprocket. Changing the number of teeth in the third sprocket also allows the third sprocket to turn at a different speed.

6.3.5.3 Gears

Gears are unique in that each pair will change the direction of rotation (Fig. 6.6).

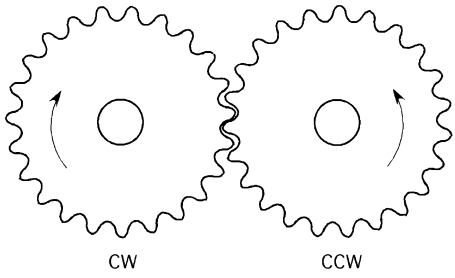


Fig. 6.6 Changing the direction of rotation with gears

6.3.6 *Complex Powertrains*

Many machines use powertrains that are more complex than what has been discussed up to this point. Fig. 6.7 represents a powertrain designed to allow an engine or motor to supply the power to two different components. These components are attached to output shafts A and B. This figure illustrates the modification of direction and speed of rotation in complex powertrains.

Problem Determine the speed and the direction of rotation for shaft A and shaft B in Fig. 6.7?

Solution In this powertrain the output shaft of a 50-horsepower motor powers gear 1. Gear 2 is powered by gear 1, and because gear 3 is attached to the same shaft, it is also powered by gear 1. Gear 4 is powered by gear 3, and gear 5 by gear 4. Shaft A will turn at the same speed and direction of rotation as gear 5, and shaft B will turn at the same speed and direction of rotation as gears 2 and 3.

More than one approach can be used to determine the speed of shaft A and shaft B. The first one shown uses the gear equation. Because there is more than one pair of gears, the equation must be used more than once. The speed of gear 2 is:

$$N_2 = \frac{T_1 \times N_1}{T_2} = \frac{24 \times 2200}{12} = 4400 \text{ rpm}$$

Because gear 2 is fixed to shaft B, shaft B and gear 3 turn at 4400 rpm.

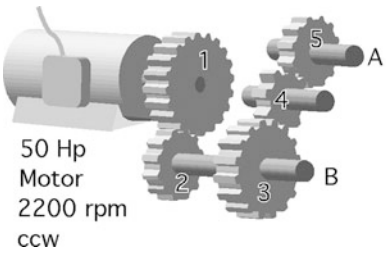
To determine the speed of shaft A, the gear equation is used for each pair of gears. First the speed of gear 4:

$$N_4 = \frac{16 \times 4400}{8} = 8800 \text{ rpm}$$

and then the speed of gear 5:

$$N_5 = \frac{8 \times 8800}{12} = 5866.66 \ldots \text{ or } 5900 \text{ rpm}$$

Therefore, shaft A turns at 5900 rpm.



Gear	Number of teeth
1	24
2	12
3	16
4	8
5	12

Fig. 6.7 Calculating shaft speed and direction of rotation in multiple shaft drives

An alternative solution is to use speed ratios. If the speed of shaft B is determined by the speed of the driver gear times the gear ratio of the two gears, then the speed of shaft B can be determined by:

$$N_B = N_1 \times \frac{T_1}{T_2} = 2200 \times \frac{24}{12} = 4400 \text{ rpm}$$

and the speed of shaft A can be determined by:

$$\begin{aligned} N_A &= N_1 \times \frac{T_1}{T_2} \times \frac{T_3}{T_4} \times \frac{T_4}{T_5} \\ &= 2200 \times \frac{24}{12} \times \frac{16}{8} \times \frac{8}{12} \\ &= \frac{6758{,}400}{1152} \\ &= 5866.66 \ldots \text{ or } 5900 \text{ rpm} \end{aligned}$$

When the speed ratio approach is used, it is important to place the number of teeth of the driver in the numerator and the number of teeth of the driven in the denominator.

The best way to determine the direction of rotation of shafts A and B is to use intuitive reasoning.

We know, from our discussion of gears, that the direction of rotation changes with every pair of gears in the powertrain. The motor turns CCW and shaft B is driven by one pair of gears. Shaft B turns clockwise. Shaft A is powered by three pairs of gears and changes the direction of rotation three times. Shaft A turns clockwise also. Study Fig. 6.8 to check these answers.

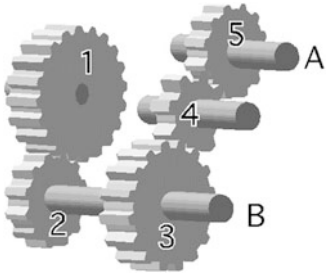


Fig. 6.8 Determining the direction of rotation for shafts *A* and *B*

6.3.7 *Speed and Torque*

In this section, speed refers to the rate of rotation and torque is a rotating force. By definition, torque is a force working through a lever arm. In powertrains speed, torque and horsepower are interdependent. To illustrate this relationship, speed and torque are explained in more detail.

In the case of belts and pulleys, the force is the tension on the belt, and the length of the lever arm is the radius of the pulley. Suppose that a spring scale is attached to the belt, as in Fig. 6.9, and assume that the scale reads 100.0 pounds.

Because the tension or force in the belt is constant along its length, there are 100.0 pounds of force pulling at the edge of both the driver (A) and the driven (B) pulley.

If the driver pulley has a diameter of 10.0 inches and the driven pulley has a diameter of 5.0 in., then the torque on the driver pulley shaft in Fig. 6.9 is:

$$\begin{aligned} \mathrm{To} &= F \times R \\ \mathrm{To} = F \times R &= 100.0\ \mathrm{lb} \times 5.0\ \mathrm{in} = 500\ \mathrm{lb\text{-}ft} \end{aligned}$$

and the torque on the driven shaft is:

$$\mathrm{To} = F \times R = 100.0\ \mathrm{lb.} \times 2.5\ \mathrm{in.} = 250\ \mathrm{lb\text{-}ft}$$

The torque is different on the two pulleys because pulleys behave as class 1 levers; the radius (one-half the diameter) is the length of the lever arm. A larger diameter pulley will have a longer lever arm, thus more torque on the shaft. This example also illustrates that because the belt speed (in inches per minute) is constant, the torque on the driven shaft is inversely proportional to the change in speed between the driver and driven pulleys. When the driven shaft turns at a higher speed, its torque is decreased relative to the driver shaft, and vice versa. The PTO power equation shows this relationship:

$$P_{\mathrm{Hp}} = \frac{\mathrm{To} \times N}{5252}$$

If the horsepower stays the same, an increase in speed (N) means the rpm must decrease, and vice versa. For belts and pulleys, this relationship also can be expressed as:

$$\mathrm{To}_1 \times N_1 = \mathrm{To}_2 \times N_2$$

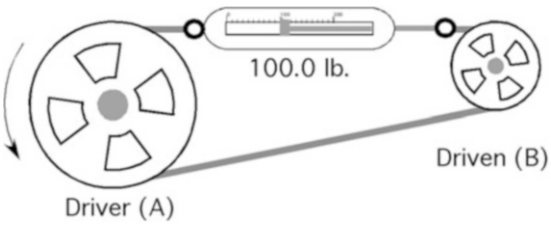


Fig. 6.9 Speed and torque

Problem The driver shaft of a belt powertrain turns at 300 rpm and applies 20.0 lb.-ft. of torque, and the driven pulley turns at 50 rpm, how much torque will be developed at the driven pulley?

Solution Rearranging the torque equation to solve for To_2:

$$To_2 = To_1 \times \frac{N_1}{N_2} = 20.0 \text{ lb} - \text{ft} \times \frac{300 \text{ rpm}}{50 \text{ rpm}} = 120 \text{ lb-ft}$$

The torque of the driven pulley will be 120 lb-ft.

Notice that the speed of the driven shaft is one-sixth that of the driver shaft, but the torque on the driven shaft is six times that of the driver shaft. This is an important concept for powertrains because a small diameter shaft can transmit a large amount of power if the speed is high. This principle is used in tractors. The rear axles of large tractors are 3 to 4 inches in diameter, but the transmission shaft that receives power from the engine is usually less than 2 inches in diameter. The axles turn at a much slower speed than the transmission shaft. The engine turns at high speed with low torque, and the drive axles turn at lower speed with higher torque.

6.3.8 *Transmission of Power and Torque*

When managing agricultural machinery, it is useful to know the amount of torque being transmitted by a component of a powertrain. For example, it would be useful to know the amount of torque and the horsepower available at shafts A and B in Fig. 6.8.

Based on the previous discussion of the relationship between torque and speed, and the torque equation, the maximum torque available at each shaft can be determined:

$$To_B = To_1 \times \frac{N_I}{N_{II}}$$

To solve for To_B, the values for the three other variables must be known. The two rpm's were calculated in the previous section. The remaining variable is the torque supplied by the motor. Horsepower will be discussed in greater detail in a later chapter, but rotary horsepower can be determined by the horsepower equation used in the previous section:

$$P_{hp} = \frac{To \times N}{5252}$$

Because the horsepower and the rpm being produced by the engine are known, the equation is rearranged to solve for engine torque:

$$To_{eng} = \frac{P_{Hp} \times 5252}{N} = \frac{50 \text{ hp} \times 5252}{2200 \text{ rpm}} = 119.36 \ldots \text{ or } 120 \text{ lb-ft}$$

Once the torque produced by the motor is known, the torque on shaft B can be calculated:

$$To_B = To_1 \times \frac{N_I}{N_{II}} = 120 \text{ lb-ft} \times \frac{2200 \text{ rpm}}{4400 \text{ rpm}} = 60 \text{ lb-ft}$$

and the torque at shaft A is:

$$\mathrm{To_A} = \mathrm{To_{motor}} \times \frac{N_{\mathrm{motor}}}{N_{\mathrm{A}}} = 120 \text{ lb-ft} \times \frac{2200 \text{ rpm}}{6000 \text{ rpm}} = 44 \text{ lb-ft}$$

Note: Because the speed of shaft A was known, the speed ratio could be used to solve for torque. If the speed of shaft A was unknown, it must be determined before starting the torque calculations.

6.3.9 Power Transmission through Powertrains

Powertrains are used to transmit power. Study Fig. 6.8 again. Can you predict how much power is available at either shaft A or shaft B? The answer 50 horsepower is correct. If we assume no frictional losses in the powertrain, power out will equal power in. This can be demonstrated by using the horsepower equation to solve for the power available at shaft A:

$$P_{\mathrm{Hp}} = \frac{\mathrm{To} \times N}{5252} = \frac{44 \text{ lb-ft} \times 6000 \text{ rpm}}{5252} = 50.26 \ldots \text{ or } 50 \text{ hp}$$

If both shaft A and Shaft B were supplying power, the sum of the power used at shaft A and shaft B would be equal to or less than 50 horsepower.

6.4 Pneumatic and Hydraulic Systems

Pneumatic and hydraulic systems are based on the behavior of a flowing liquid. The primary difference is that hydraulic oil is considered noncompressible and air is compressible. Hydraulic systems are used on more agricultural equipment than pneumatic. Therefore, the remaining discussion will concentrate on hydraulic systems. Hydraulic systems used on agricultural equipment have at least five required components (Fig. 6.10). The heart of the system is a pump. Different types of pumps are used, but they have a common job—energize the system. Hydraulic systems also require a reservoir to store the oil, control valves to control the amount and direction of flow, some type of actuator to perform the work, and hoses/pipes to connect all of the components. Other components are included as necessary to achieve the desired performance of the system.

Hydraulic systems operate on two principles, pressure and flow. Pressure results in force or torque, and flow causes movement. These principles will be explained using two pistons connected by a pipe (Fig. 6.11).

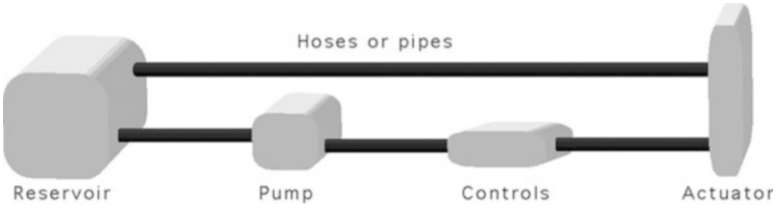


Fig. 6.10 Five required components of a hydraulic system

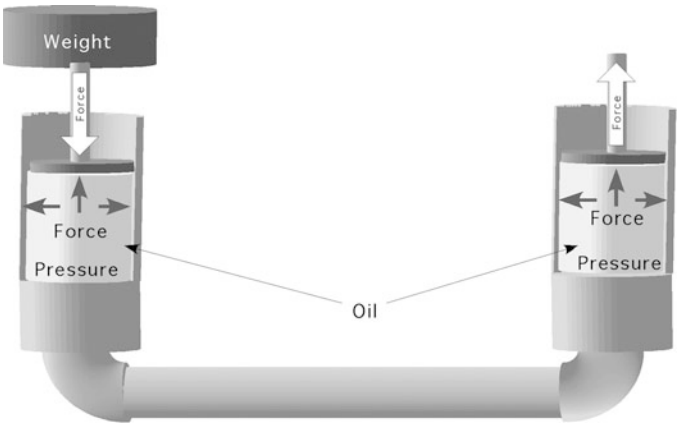


Fig. 6.11 Force: the first principle of hydraulics

6.4.1 Hydraulic Pressure

The pressure in a system is governed by Pascal's Law, which states that the pressure on a confined liquid is transmitted equally in all directions and results in equal force at right angle to the container walls.

In Fig. 6.11, gravity working through the weight connected to the piston causes a pressure in the liquid. The pressure in the liquid results in a force perpendicular to the cylinder walls. In this example, the amount of weight and the area of the piston determine the amount of force in the liquid. Expressed as an equation:

$$P = \frac{F}{A}$$

where P = Pressure, lb/in^2; F = Force, lb; A = Area, in^2.

For example, if 8.5 pounds of weight is attached to the piston, which has an area of 3.25 square inches, the pressure in the liquid is:

$$P\,\frac{\text{lb}}{\text{in}^2} = \frac{F\ (\text{lb})}{A\ (\text{in}^2)} = \frac{8.5\ \text{lb}}{3.25\ \text{in}^2} = 2.615\ldots \text{or } 2.6\,\frac{\text{lb}}{\text{in}^2}$$

The liquid has a pressure of 2.6 pounds per square inch.

The pressure in the liquid is constant throughout the system; therefore, the force at the actuator cylinder can be increased or decreased by changing the area of the piston (Fig. 6.12). The amount of force produced is determined by multiplying the pressure times the area.

$$F = P \times A$$

where P = Pressure, psi or lb/in^2; F = Force, lb; A = Area, in^2.

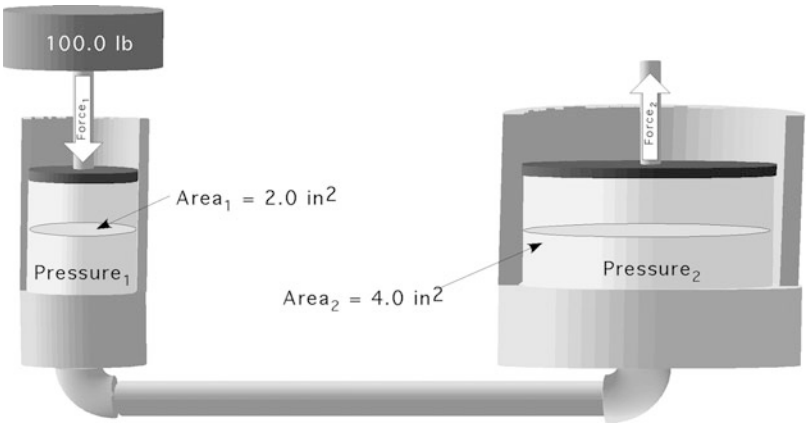


Fig. 6.12 Increasing force using hydraulics

Problem How must force is produce on the actuator piston in Fig. 6.12?

Solution The first step is to determine the pressure in the system:

$$\begin{aligned} P_1 &= \frac{F_1}{A_1} \\ &= \frac{100.0 \text{ lb}}{2.0 \text{ in}^2} \\ &= 50 \frac{\text{lb}}{\text{in}^2} \end{aligned}$$

But the pressure is the same at both cylinders. Therefore:

$$\begin{aligned} F_2 &= P_1 \times A_2 \\ &= 50 \frac{\text{lb}}{\text{in}^2} \times 4 \text{ in}^2 \\ &= 200 \text{ lb} \end{aligned}$$

When a 100.0 pound of force is applied to area of 2.0 sq inches a pressure of 50 pounds per square inch is produced. When this pressure is in contact with an area of 4.0 sq inches, a force of 200 pounds is produced. The increase or reduction of the force is proportional to the area of the piston.

A simple piston system was used to explain the principles of hydraulics. The same principles are true for a more complex system. In most mobile uses of hydraulics, the pressure is produced by a pump and regulated by a pressure relief valve. When cylinders are used, the diameter of the cylinder and the pressure of the fluid at the cylinder determine the force produced.

6.4.2 *Hydraulic Flow*

The second principle of hydraulic systems is flow. Flow is the movement of the liquid through the system. The flow rate of the fluid determines the speed of movement for the actuators in the system. In mobile systems, flow rate is measured in gallons or liters per minute, but any volume unit per unit time can be used.

In a two-piston system as illustrated in Fig. 6.13, the total flow (in^3) from the first piston to the second can be determined by multiplying the area (in^2) of the piston times the length (in) of the stroke (S). The distance the resultant piston moves is a function of the diameter of the resultant piston. If the second piston has a larger area, the distance moved will be less. If the second piston area is smaller, the distance moved will be greater. This relationship can be expressed mathematically:

$$A_1 \times S_1 = A_2 \times S_2$$

where A_1 = area of piston one, in^2; S_1 = the distance piston one moves, in; A_2 = area of piston two, in^2; S_2 = the distance piston two moves, in.

Problem How far will the actuator piston in Fig. 6.13 move?

Solution Rearrange the equation to solve for S_2:

$$\begin{aligned} A_1 \times S_1 &= A_2 \times S_2 \\ S_2 &= \frac{A_1 \times S_1}{A_2} \\ &= \frac{2.0\ \text{in}^2 \times 6.0\ \text{in}}{4.0\ \text{in}^2} \\ &= 3.0\ \text{in} \end{aligned}$$

The resultant piston will move 3.0 inches.

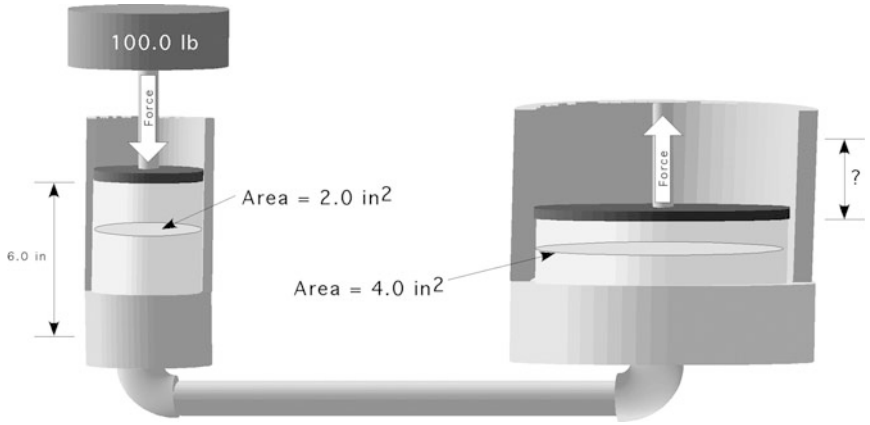


Fig. 6.13 Relative movement example

The distance the cylinder extends or retracts is determined by the amount of fluid that moves, and the speed at which the cylinder extends or retracts is determined by the flow rate of the fluid.

Problem Determine the actuator force, the movement (in), and the rate of movement (in/min) for a 3.50 inch diameter cylinder when the system pressure is set at 2500 pounds per square inch (psi), the flow rate is 3.25 gallons per minute (gpm), and the control valve is activated for 25.0 s.

Solution The process for determining the resultant force is the same as the one used in the previous problem:

$$\begin{aligned} F\ (\text{lb}) &= P\left(\frac{\text{lb}}{\text{in}^2}\right) \times A\ \left(\text{in}^2\right) \\ &= 2500\,\frac{\text{lb}}{\text{in}^2} \times \left(\pi \times (1.75\ \text{in})^2\right) \\ &= 2500\,\frac{\text{lb}}{\text{in}^2} \times 9.621\ldots\,\text{in}^2 \\ &= 24{,}052.818\ldots \text{ or } 24{,}000\ \text{lb} \end{aligned}$$

Assuming no friction losses, the cylinder will produce 24,000 pounds of force.

The amount of extension or stroke is a function of the cross-sectional area of the cylinder and the volume of fluid flow. This problem will be solved using the unit cancelation method:

$$\begin{aligned} S(\text{in}) &= \frac{231\ \text{in}^3}{1\ \text{gal}} \times \frac{3.25\ \text{gal}}{1\ \text{min}} \times \frac{1\ \text{min}}{60\ \text{sec}} \times \frac{25.0\ \text{sec}}{1} \times \frac{1}{9.6211\ldots\,\text{in}^2} \\ &= \frac{18{,}768.75}{577.26} = 32.513\ldots \text{ or } 32.5\ \text{in E2} \end{aligned}$$

The actuator will extend 32.5 inches.

The flow rate of the fluid (Q) and the cross-sectional area of the cylinder determine the rate of movement. This problem can also be solved using the unit cancelation method:

$$V\left(\frac{\text{in}}{\text{min}}\right) = \frac{231\ \text{in}^3}{1\ \text{gal}} \times \frac{3.25\ \text{gal}}{1\ \text{min}} \times \frac{1}{9.6211\ \text{in}^2} = \frac{750.75}{9.6211} = 78.031\ldots \text{ or } 78.0\ \frac{\text{in}}{\text{min}}$$

With a flow rate of 3.25 gallons per minute and an actuator area of 9.621 sq inches the actuator piston will move at the rate of 78.0 inches per minute.

6.4.3 Metric Problems

Problem What diameter of pulley is needed if the desired speed is 500 rpm and the driven pulley is 6.0 cm and turns at 1725 rpm?

Solution

$$D_1 \times N_1 = D_2 \times N_2$$

$$D_2 = \frac{D_1 \times N_1}{N_2} = \frac{6.0 \text{ cm} \times 1725 \dfrac{\text{rev}}{\text{min}}}{500 \dfrac{\text{rev}}{\text{min}}} = \frac{10{,}350}{500} = 20.7 \text{ or } 21 \text{ cm}$$

The driven pulley should have a diameter of 21 cm.

Problem Determine the torque available at shafts A and B in the illustration (Fig. 6.14).

Solution The first step is to determine the speeds of shafts A and B. Shaft B is the first one in the series so it will be used first:

$$T_1 \times N_1 = T_2 \times N_2$$

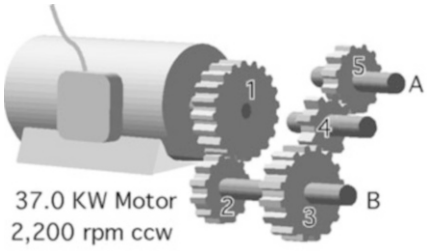
$$N_B = \frac{T_1 \times N_1}{T_2} = \frac{24 \text{ T} \times 2200 \dfrac{\text{rev}}{\text{min}}}{12 \text{ T}} = \frac{52{,}800}{12} = 4400 \text{ rpm}$$

The speed of shaft B is 4400 revolutions per minute.

The speed of shaft A:

$$\begin{aligned} N_A &= N_1 \times \frac{T_I}{T_{II}} \times \frac{T_{III}}{T_{IV}} \times \frac{T_{IV}}{T_V} \\ &= 2200 \times \frac{24}{12} \times \frac{16}{8} \times \frac{8}{12} \\ &= \frac{6{,}758{,}400}{1152} \\ &= 5866.66 \ldots \text{ or } 5900 \text{ rpm} \end{aligned}$$

The speed of shaft A is 5900 revolutions per minute.



Gear	Number of teeth
1	24
2	12
3	16
4	8
5	12

Fig. 6.14 Complex powertrain with metric values

The maximum torque will be available at only one shaft at a time. The maximum torque can be calculated for either A or B. The first step is to determine the torque produced by the motor. The maximum torque delivered by the motor is:

$$P_{\text{kW}} = \frac{\text{To} \times N}{9549}$$

solving for torque (T_{o}):

$$\begin{aligned} \text{To} &= \frac{9549 \times P_{\text{kW}}}{N} \\ &= \frac{9549 \times 37.0}{2200} \\ \text{To} &= 160.6 \text{ Nm} \end{aligned}$$

The motor is producing 160.6 newton meters of torque.

The torque that could be produced at shaft A is:

$$\begin{aligned} \text{To}_1 \times N_{01} &= \text{To}_2 \times N_2 \\ \text{To}_2 &= \frac{\text{To}_1 \times N_1}{N_2} \\ &= \frac{160.6 \text{ Nm} \times 2200 \frac{\text{rev}}{\text{min}}}{5900 \frac{\text{rev}}{\text{min}}} \\ &= \frac{353{,}320}{5900} = 59.884 \ldots \text{or } 60 \text{ Nm} \end{aligned}$$

The torque that could be produced at B is:

$$\begin{aligned} \text{To}_2 &= \frac{\text{To}_1 \times N_1}{N_2} \\ &= \frac{160.6 \text{ Nm} \times 2200 \frac{\text{rev}}{\text{min}}}{4400 \frac{\text{rev}}{\text{min}}} \\ &= \frac{353{,}320}{4400} = 80.3 \text{ Nm} \end{aligned}$$

Shaft B could produce a torque of 80.3 newton meters.

Problem How much force will be produced by the hydraulic system in Fig. 6.15 when the diameter of the first cylinder is 5 cm, the diameter of the second cylinder is 15 cm, and the force on the first cylinder is 50 kN?

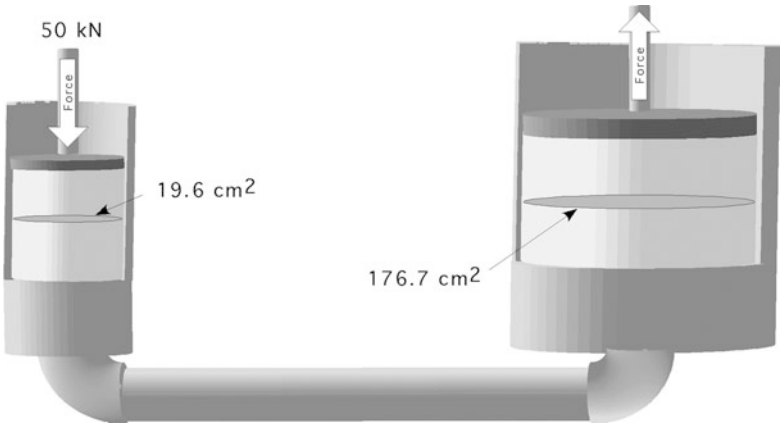


Fig. 6.15 Force produced using SI units

Solution Force divided by area equals pressure and pressure multiplied by area equals force.

$$
\begin{aligned}
P(\text{kPa}) &= \frac{F(\text{N})}{A\ (\text{cm})} \\
&= \frac{50\ \text{kN}}{\frac{\pi \times (5\ \text{cm})^2}{4}} \times \frac{10{,}000\ \text{cm}^2}{1\ \text{m}^2} \times \frac{1000\ \text{N}}{1\ \text{kN}} \times \frac{1\ \text{Pa}}{\text{N}/\text{m}^2} \times \frac{1\ \text{kPa}}{1000\ \text{Pa}} \\
&= \frac{500{,}000{,}000}{19{,}634.95\ldots} = 25{,}464.79\ldots \text{ or } 25{,}000\ \text{kPa} \text{ or } 25\ \text{MPa}
\end{aligned}
$$

The pressure on the fluid will be 25,000 kilopascals. The force produced by the second cylinder is:

$$
\begin{aligned}
F(\text{N}) &= P\,(\text{kPa}) \times A\ (\text{cm}^2) \\
&= 25{,}000\ \text{kPa} \times \frac{\pi \times (15\ \text{cm})^2}{4} \times \frac{1\ \text{m}^2}{10{,}000\ \text{cm}^2} \\
&\quad \times \frac{1000\ \text{Pa}}{1\ \text{kPa}} \times \frac{\text{N}/\text{m}^2}{1\ \text{Pa}} \times \frac{1\ \text{kN}}{1000\ \text{N}} \\
&= \frac{417{,}864{,}669}{10{,}000{,}000} = 441.786 \text{ or } 440\ \text{kN}
\end{aligned}
$$

The second cylinder will produce a force of 440 kilonewtons.

Problem How far will the resultant piston in the previous problem move when the piston in the first cylinder moves 5 cm?

Solution area × stroke distance = area × stroke distance

$$
\begin{aligned}
A_1 \times S_1 &= A_2 \times S_2 \\
S_2 &= \frac{A_1 \times S_1}{A_2} \\
&= \frac{19.6\ \text{cm}^2 \times 5\ \text{cm}}{176.7\ \text{cm}^2} \\
&= \frac{98}{176.7} = 0.554 \ldots \text{or } 0.55\ \text{cm}
\end{aligned}
$$

Chapter 7
Tractors and Power Units

7.1 Objectives

1. Be able to describe the common designs of tractors
2. Be able to estimate drawbar and PTO power using the 86% rule
3. Be able to derate a stationary power unit for the intended work environment
4. Be able to explain the concept of lugging ability
5. Be able to describe the principles of tractor testing
6. Be able to understand the ASAE and OECD tractor-testing procedures

7.2 Introduction

A tractor is a very versatile machine, but the range of uses is too wide for one size or type of tractor to be optimum for all possible jobs. Tractor manufacturers target individual tractor designs for specific uses. These uses have been categorized by type and size, but the boundaries are not ridged. Problems can arise if operators push the boundaries too far. Using a tractor that is too small or too large for the job can cause malfunctions and breakdowns. Using a tractor for a job that it was not designed for can also lead to problems. In these situations, the tractor can fail which may cause an accident for the operator or bystander. It is important for the owner/operator to have a basic understanding of the common categories of tractors. This chapter will also explain how stationary engines and tractors are derated, and how tractors are tested.

7.3 Categories of Tractors

The diversity of modern agriculture requires different tractor designs. Historically, utility (use) has been the basis of tractor classification schemes. Based on utility, there are six categories of tractors:

1. General purpose
2. Row crop

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H.L. Field, J.M. Long, *Introduction to Agricultural Engineering Technology*,
https://doi.org/10.1007/978-3-319-69679-9_7

3. Orchard
4. Vineyard
5. Industrial
6. Garden

The boundaries for these categories are more blurred today because a single model of modern tractor is designed to have the broadest possible number of uses. It is more common to classify modern agricultural tractors by their category of three-point hitch. The American Society of Agricultural and Biological Engineers (ASABE) uses five categories of tractors based upon rated engine horsepower. (Table 7.1).

The three-point hitch was patented by Harry Ferguson in the 1920s to improve the way implements were attached to tractors. Before the three-point hitch, most implements were attached to the drawbar. The three-point hitch had two primary advantages.

1. It used tractor power to lift implements out of the ground which was a big advantage over the mechanical trip systems in use.
2. Plows and similar implements provided a downforce on the rear axle of the tractor. This downforce improves the traction for the tractor.

To classify a tractor using either the utility categories and/or the hitch categories, the propulsion system must also be identified. The five propulsion systems are:

1. Rear-wheel drive (RWD)
2. Four-wheel drive articulating steering (4WDAS)
3. Four-wheel drive four-wheel steer (4WD)
4. Tracks (T)
5. Rear-wheel drive with front wheel assist (FWA)

Each of the six utility categories will be explored in more detail.

7.3.1 General Purpose

The general-purpose tractor is the traditional design with two rear wheels and two front wheels spaced the same distance apart. This type of tractor usually is built closer to the ground than the row crop design. The power range of tractors of this type is very broad; sizes range from about 25 to over 400 horsepower (19–300 kW). The use of a general-purpose tractor is influenced by its power. The smaller sizes

Table 7.1 Three-point hitch categories

Category	Horsepower
0	0–20
1	20–45
2	40–100
3	80–225
4	180+

are very popular for smaller agricultural enterprises. They are often called loader and mower tractors. The mid-range sizes are used extensively for cultivating, spraying, tilling, and mowing. They can also be used with loaders and mowers and for mobile or stationary power take-off (PTO) power. The larger sizes normally are used for primary tillage and to provide PTO power for larger mobile and stationary machines such as large balers, forage harvesters, emergency generators, and silage blowers. Some of the tractors at the top of the power range are designed for tillage only and may not have a PTO or three-point hitch.

General-purpose tractors are available with all five types of propulsion systems. Historically, this tractor category was primarily rear-wheel drive, but in recent years, front wheel assist has become very popular. The propulsion system also is influenced by the power. Smaller tractors use the rear-wheel drive or the front wheel assist; in the middle of the power range, all types can be found; and in the largest engine sizes, articulating four-wheel drive configurations have historically been the only choice, but quad track configurations are becoming a popular option.

7.3.2 Row Crop

Row crop tractors are designed with greater ground clearance than general-purpose tractors because they are designed to straddle row crops. This gives them the ability to straddle taller crops when cultivating or spraying with less plant damage. The size range of row crop tractors is narrower than that of the general purpose, as these tractors are usually 50–100 horsepower (37–75 kW). Historically they were built with the front wheels closer together than the rear wheels (tricycle style), but today most have the same wheel width. Narrow front wheels eliminate the use of tracks, front wheel assist, and articulating steering.

7.3.3 Orchard

As the name implies, orchard tractors are designed to be used around trees in orchards. They are not a separate type of design, as general purpose and row crop, but are tractors that have been modified to reduce the possibility of tree limbs catching on them as they pass by. Modifications can include using smaller tires, changing the location of the exhaust and the air intake and the addition of shields around the tires and other protuberances to reduce limb breakage. Orchard work is not as power demanding as primary tillage; therefore, these tractors are usually in the medium power sizes.

7.3.4 Vineyard

Vineyard tractors are in the smaller power range. They have been designed or modified to reduce the width so they can pass between narrow rows. Vineyards are planted on steep slopes so these tractors also have a low center of gravity. They also

may use shielding similar to that of the orchard tractor. The narrower size limits and the desire for low center of gravity makes tracks popular, but conventional rear axle drive and front wheel assist are also produced.

7.3.5 Industrial

Industrial tractors may be general-purpose agricultural tractors that have been modified to function in industrial environments or they may be special built. They may be equipped with tires designed for use on hard, smooth surfaces. The axles and frames are usually designed to withstand the weight and shocks of front loaders, backhoes, and other industrial equipment.

7.3.6 Garden

This tractor category has the greatest amount of variation in design. These tractors are usually less than 25 horsepower. Some look like a small agricultural tractor, but others may look more like a riding lawn mower. They generally use the rear-wheel drive system, with or without front wheel assist.

7.4 Tractor Power Ratings

Different power ratings are used to evaluate the size of tractors. It is important to remember that it is advantageous for manufactures to advertise their tractors with the highest possible horsepower to make them more competitive in the marketplace. The useable power is usually less than the advertised power. The rating used to express the power must be known before the useable power can be determined, Fig. 7.1.

The following sections will explain the four common power ratings for tractors.

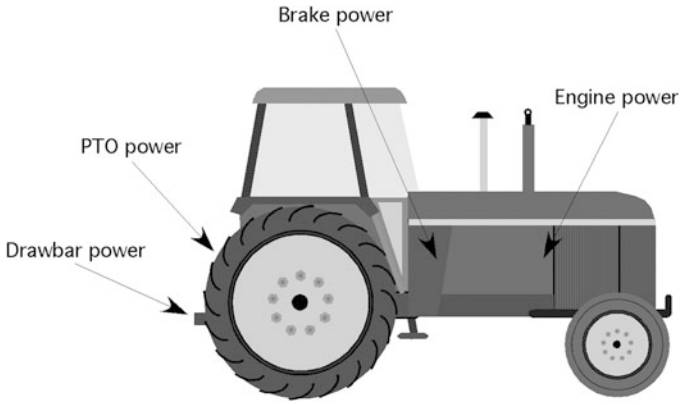

Fig. 7.1 Tractor power ratings

7.4.1 Engine Power

Engine power is a calculated, theoretical, power based on the bore, mean cylinder pressure, and speed of the engine. Engine power is not a useful rating for determining the useable power available from a tractor or stationary engine, but it is sometimes used in advertisements.

7.4.2 Brake Power

The term brake power comes from the early use of the Prony brake to measure engine power. The Prony brake measured the power at the belt pulley of the tractor. Today, brake power is used to describe the power available at the flywheel of the engine. Brake horsepower shouldn't be used to size tillage implements or for PTO power requirements but can be used to compare tractors. It is useful for rating engines used for irrigation pumps and other stationary power uses.

7.4.3 PTO Power

Power take-off power is a rating of the power available at the power take-off of an agricultural tractor. PTO power is determined using a dynamometer. Power take-offs are used to supply rotary power to many different types of machines such as balers, pumps, and mowers. Power take-off power can be determined using either one of the following power equations:

$$P = \frac{T_o \times N}{5252}$$

where P = power, hp; T_o = torque, lb.-ft.; N = speed, rpm; 5252 = conversion constant, or

$$P = \frac{T_o \times N}{t \times 9549}$$

where P = power, kw; T_o = torque, Nm; N = speed, rpm; t = time, s.

7.4.4 Drawbar Power

Drawbar power is the tractor power measured at the point implements that are attached to the tractor, drawbar, or three-point hitch. During tractor testing, a load cell is placed between the tractor and a load to determine the amount force, or pull, produced by the tractor. During the test, the drawbar force and the speed of travel is recorded. The force is measured in pounds/newtons, and the velocity is measured miles per hour/kilometers per hour. The equation for English units is:

$$Db_{Hp} = \frac{F \times V}{375}$$

where F = Force (lb); V = Speed (mph); 375 = Units conversion constant.

This equation is a modification of the standard power equation $P_{\text{Hp}} = \frac{F \times D}{\text{t} \times 33{,}000}$. Velocity (V) $= \frac{\text{Distance (D)}}{\text{time (t)}}$ and 1 $\frac{\text{mile}}{\text{hr}} = 88$ $\frac{\text{ft}}{\text{min}}$, then 1 hp $= \frac{F \times V \times 88}{33{,}000} = \frac{F \times V}{375}$.

Problem How much drawbar power is a tractor producing if it develops 1,500 pounds of force at a speed of 5.5 miles per hour?

Solution

$$Db_{\text{Hp}} = \frac{F \times V}{375} = \frac{1500 \text{ lb} \times 5.5 \dfrac{\text{mile}}{\text{h}}}{375} = \frac{8250}{375} = 22 \text{ hp}$$

A tractor traveling at 5.5 miles per hour while producing 1500 pounds of pull is developing 22 horsepower.

7.4.5 Converting Tractor Power Ratings

Manufactures can use any of the four power ratings to advertise tractors. When manufactures use engine or brake power, to rate a tractor, they are not providing useful information because the useable power will be less. When the tractor is rated by engine or brake power, the PTO power will be less because of the losses in the power train. The drawbar power will be less because there are additional losses in the transmission and drive train and a tractor is not able to apply all of the torque of the drive wheels to the soil.

Power take-off and drawbar power ratings are available if the tractor has been tested by the Nebraska Tractor Test Laboratory (NTTL) or by the Organization for Economic Cooperation and Development (OECD). These two organizations measure the drawbar and PTO horsepower for production tractors. When actual PTO and drawbar ratings are not available, the 86% rule can be used to estimate them from the engine rating.

Studies have shown that if a large number of tractors are compared over many different traction conditions, the PTO power will be approximately 86% of the engine power, and the drawbar power will be approximately 86% of the PTO power. The 86% rule provides an estimate of PTO and drawbar power when the engine horsepower is known. It is not intended to be a substitute for actual data.

Problem Estimate the amount of power available at the PTO and the drawbar for a tractor rated at 125.0 engine power (E_{Hp}).

Solution Using the 86% rule:

$$\text{PTO}_{\text{Hp}} = E_{\text{Hp}} \times 0.86 = 125.0 \text{ hp} \times 0.86 = 107.5 \text{ PTO}_{\text{Hp}}$$

A tractor with 125 engine horsepower will have approximately 110 horsepower at the PTO:

$$Db_{\text{Hp}} = \text{PTO}_{\text{Hp}} \times 0.86 = 107.5 \text{ PTO}_{\text{Hp}} \times 0.86 = 92.45 \text{ or } 92.4 \text{ Db}_{\text{Hp}}$$

A tractor with 125 engine horsepower will have approximately 94.6 drawbar horsepower.

When the desire is to know just drawbar horsepower from engine horsepower, the 86% can be combined in one equation:

$$Db_{Hp} = E_{Hp} \times 0.86 \times 0.86 = 125.0 \times 0.86 \times 0.86 = 92.45 \text{ or } 92.4\ Db_{Hp}$$

The 86% rule can be used in other ways. For example, if the drawbar power is known, the PTO and engine power can be estimated.

Problem What is the estimated PTO power if the tractor produces 50.0 power at the drawbar?

Solution From the discussion of the 86% rule, we know that the PTO power will be larger than the drawbar. Therefore:

$$PTO_{Hp} = \frac{Db_{Hp}}{0.86} = \frac{50.0\ Db_{Hp}}{0.86} = 58.139\ldots \text{ or } 58\ PTO_{Hp}$$

7.4.6 Lugging Ability

An important feature of tractor engines used for primary tillage or as a stationary power supply is their lugging ability. Lugging ability is a measure of the amount of temporary overload the tractor can withstand without stalling the engine. The lugging ability for a tractor or stationary engine is illustrated in the horsepower curve shown in Fig. 7.2. This engine is designed to operate at 2050 rpm. As the engine is overloaded, the rpm drops from the top engine speed. Follow the power curve to the left and note that from 2050 rpm to 1850 rpm, the power increases. This is typical for tractor engines.

The amount of increase in power is a measure of the engines lugging ability.

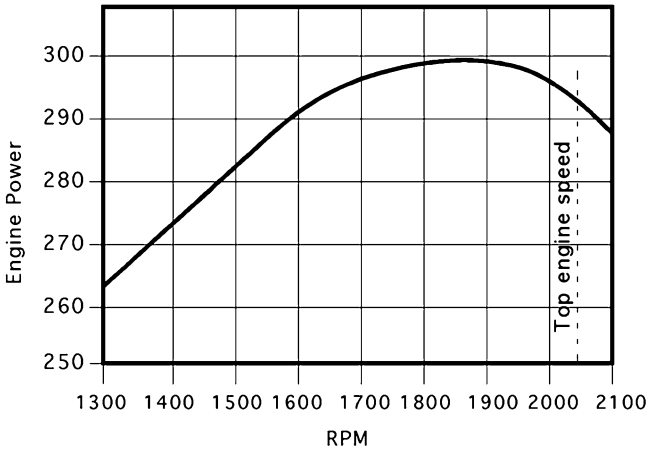

Fig. 7.2 Engine power curve with lugging ability

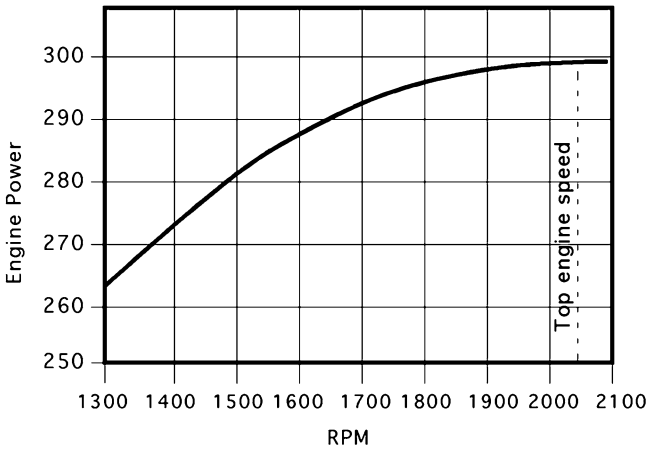

Fig. 7.3 Engine power curve with no lugging ability

Compare the power curve in Fig. 7.2 with the power curve in Fig 7.3.

This engine does not have lugging ability because the power decreases as soon as the rpm decreases. There is no temporary increase in power to help the tractor pull through a temporary overload. This power curve is typical for many small engines used on lawn mowers.

7.4.7 Derating Power Units

Derating an engine is determining the useable power from the rated or indicated power. Engines providing power for stationary loads need to be derated. Two examples of stationary loads are pumps and generators. The need for and principles of derating should also be considered when using a tractor as a stationary power source. The factors used for derating an engine depend on the engine type and the operating environment. These factors include:

1. Accessories
2. Temperature
3. Altitude
4. Type of service

These factors must be considered because the published power ratings for engines designed for stationary loads are usually tested without any accessories, at room temperature and at atmospheric pressure close to sea level. The type of service refers to continuous duty or noncontinuous duty. Continuous duty is a load that doesn't vary in RPM or power demand.

Manufacturers of engines designed for stationary duty publish performance curves for their engines, Fig. 7.4.

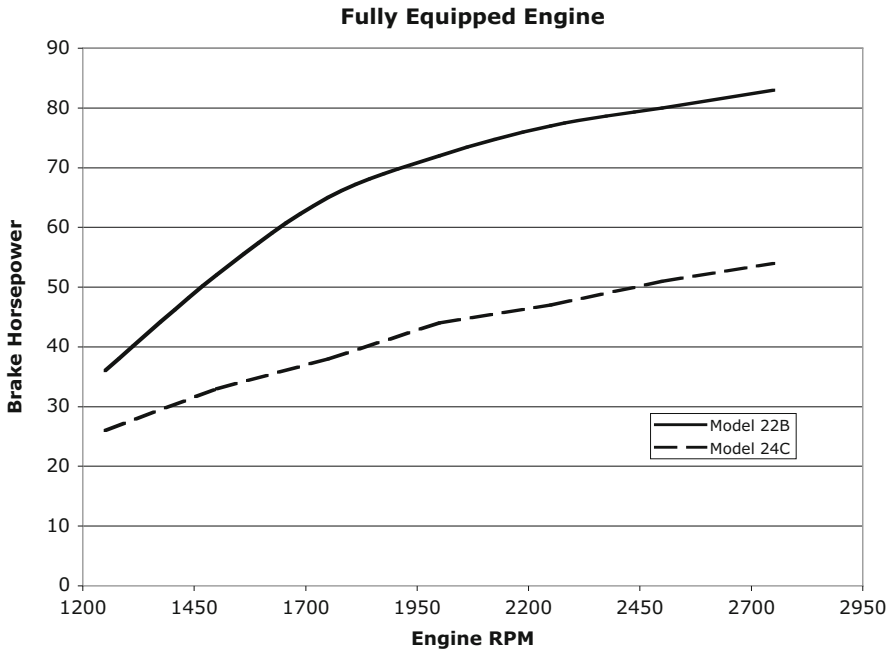

Fig. 7.4 Engine performance curves

Pumps, generators, and similar loads are designed to operate at a specified speed. If the desired speed is 2200 rpm, then the model 24C engine in Fig. 7.4 would provide about 45 horsepower. Using this engine to power a 45 horsepower pump or generator will shorten the life of the engine. If only these two engines were available, the model 22B engine should be used. The 22B engine at 75 horsepower is probably too large, but the only way to know for sure is to calculate the derated horsepower.

The following sections will discuss the derating factors in more detail and show how they are used.

7.4.7.1 Accessories

When the power rating is reported for a basic engine, sometimes called the net power rating, all the accessories are removed when it was tested. These accessories include the air cleaner, muffler, generator, governor, fan, radiator, and sometimes the water pump. The engine is tested without these accessories because they all require power. When the power rating is for a fully equipped engine, sometimes called a gross power rating, the accessories were installed on the engine when it was tested.

When basic engine power is reported, the engine must be derated 10% for all accessories other than the fan. An additional 5% must be deducted if the engine will have a fan and a radiator instead of a heat exchanger.

Problem How much useable power is available if the basic engine rating is 75.0 hp for an engine that will have all the typical accessories, a fan and a radiator?

Solution Derating 10% for the accessories and 5% for the fan:

$$\text{hp} = 75.0\ \text{hp} \times (1.0 - (0.10 + 0.05)) = 75.0 \times 0.85 = 63.75 \text{ or } 64\ \text{hp}$$

The engine will have 64 useable horsepower.

This problem can also be solved by summing the power loss for each factor, calculating the total power lost, and subtracting the loss from the initial power rating:

$$\begin{aligned}\text{hp} &= 75.0\ \text{hp} - \text{Loss} = 75.0\ \text{hp} - (75.0 \times (0.10 + 0.05)) \\ &= 75 - 11.25 = 63.75 \text{ or } 64\ \text{hp}\end{aligned}$$

The effect of accessories and fan is to reduce the useable power from 75 to 64 horsepower.

7.4.7.2 Temperature

Air temperature must be considered when determining useable power because the density of air decreases as the temperature of air increases. Less dense air has less oxygen per cubic foot. Decreasing the oxygen content of the air will decrease power produced by an engine. The important air density is the density of the air as it enters the engine. For turbocharged and supercharged engines, the density of the air has been increased above ambient removing the negative effect of temperature. Therefore no adjustment for temperature needs to be completed.

For naturally aspirated spark ignition engines, the power rating must be reduced 1% for each 10 °F (5.6 °C) ambient temperature increase above 85 °F (29 °C). For diesel engines, the adjustment is 1% for each 5 °F (2.7 °C) above 85 °F (29 °C).

Problem Determine the useable power for a 165.0 Bhp spark ignition engine. The engine will be operating in 100.0 °F air temperature.

Solution Using the recommended derating for temperature:

$$\begin{aligned}\text{hp} &= 165.0\ \text{hp} \times \left(1 - \left(0.01 \times \frac{100\ \text{F} - 85\ \text{F}}{10\ \text{F}}\right)\right) = 165.0 \times 0.985 \\ &= 162.525 \text{ or } 160.5\ \text{hp}\end{aligned}$$

The effect of the 100 °F temperature is to reduce the useable power from 165.0 to 160.5 horsepower.

7.4.7.3 Altitude

Barometric pressure decreases with altitude. A reduction in pressure also reduces the efficiency of naturally aspirated engines. As the elevation of the engine increases, the pressure difference is less between the air pressure inside the cylinder, on the intake stroke, and the atmospheric pressure. Decreasing the pressure difference decreases the amount of air that flows into an engine during the intake stroke.

Altitude is not a problem for engines with turbochargers or superchargers because they increase the intake system pressure above atmospheric pressure. For naturally aspirated spark ignition and diesel engines, the power rating must be reduced by 3% for each 1000 feet (305 m) of elevation above 500 feet (152 m) above sea level.

Problem What is the useable power rating for a 225.0 hp naturally aspirated diesel engine operating at an elevation of 4500 feet above sea level?

Solution Using the derating recommendation for altitude: (Note: The method used to solve this example is different from the previous one. Either method can be used.)

$$\begin{aligned} E_{\mathrm{Hp}} &= 225.0\ \mathrm{hp} \times \frac{100\% - \left(3.0\% \times \left(\frac{4500\ \mathrm{ft} - 500\ \mathrm{ft}}{1000}\right)\right)}{100} \\ &= 225\ \mathrm{hp} \times 0.88 \\ &= 198\ \mathrm{hp} \end{aligned}$$

The diesel engine useable horsepower will be reduced from 225 horsepower to 198 horsepower because of the effect of altitude.

7.4.7.4 Type of Service

Engine service types are categorized as intermittent or continuous loads. The load on tractors pulling tillage equipment in the field is classified as an intermittent load because the drawbar pull of the tillage equipment varies as it travels through the field. Continuous loads provide little variation in the torque and speed demands placed on the engine. Examples of continuous loads are irrigation pumps and generators. Manufacturers may indicate the type of service for the rated power, if not the engine should be derated for the type of service. The available power must be reduced by 10% for intermittent loads and 20% for continuous loads.

Problem What is the useable power for an engine that has been derated for accessories, temperature, and altitude to 115.3 hp if it will be used to power a continuous duty load?

Solution Derating for continuous duty:

$$\text{hp} = 115.3\ \text{hp} \times \left(\frac{100\% - 20\%}{100}\right) = 115.3 \times 0.80 = 92.48 \text{ or } 92\ \text{hp}$$

A 115.3 horsepower engine operating a continuous duty load should be derated to 92 horsepower.

From the previous discussion, it is evident that an important difference may exist between rated power and useable power for stationary engines. If a tractor is being used for stationary power for an extended period of time, it should be derated also. When derating a tractor, remember that the PTO power will be equal to that of a fully equipped engine.

The previous section explained the procedure for derating an engine for individual factors. One question that remains is how is an engine derated when more than one factor is involved. The recommended method is to sum up the reduction for each individual factor and multiply this number by the initial power rating.

Problem Determine the useable power for a fully equipped, turbocharged diesel engine rated at 115.0 horsepower when it is operated on continuous duty, at 3350 feet elevation and at an air temperature of 98.5 degrees Fahrenheit.

Solution For this example, the engine must be derated for temperature and service. It does not need to be derated for altitude because it is turbocharged.

Temperature:

$$1\% \times \left(\frac{98.5\ \text{F} - 85\ \text{F}}{5\ \text{F}}\right) = 2.7\%$$

Service:

Continuous duty requires a derating of 20%.

Total adjustment:

$$\text{Total} = \text{temperature} + \text{duty} = 2.7\% + 20\% = 22.7\%$$

The total reduction is:

$$E_{\text{Hp}} = 115.0\ \text{hp} \times \left(1 - \frac{22.7}{100}\right) = 88.895 \text{ or } 88.9\ \text{hp}$$

A 115.0 power engine operating under these conditions will have 88.9 useable power.

7.5 Tractor Testing

Early tractors were designed to deliver power in three ways: by belt pulley, by drawbar, and by power take-off. Belt pulleys have been eliminated from tractors manufactured in the United States. One problem the owner/manager has faced since the first tractor was designed is lack of information on the power ratings of tractors. As a rule, tractor manufacturers do not advertise the drawbar or PTO ratings of their tractors; instead many use brake power or engine power. If engine power is used, it could be a theoretical power rating for the engine.

In 1918, the Nebraska legislature passed a law that established the Nebraska Tractor Test Laboratory. This law mandated that a typical model of tractor must be tested before it could be sold within the state of Nebraska and that the manufacturer must maintain a parts supply depot within the state. This testing station has provided the only independent evaluation of tractors in the United States.

As time passed and a large percentage of tractor manufacturing moved outside the United States, the law was changed. Today tractors can be sold in Nebraska with either a NTTL or an OECD test. The Nebraska test procedures were changed to match the standards established by the Society of Automotive Engineers (SAE) and the American Society of Agricultural and Biological Engineers (ASABE). Currently the Nebraska Tractor Test Station is qualified to conduct either test at the request of the tractor manufacturer. A full review of both testing standards is not possible in this text. The following is a discussion of the general principles of testing and the two test methods. Individual reports and additional information can be obtained from the testing stations[1,2].

7.5.1 Principles of Testing

Accurate information is a must for efficient management of modern farms and ranches. The main objective of both testing methods is to provide an unbiased result that allows comparisons to be made between different models or tractors and different years. The tractor-testing standards establish the test conditions and the rules of behavior for the manufacturer and the testing station during the testing.

It should be evident that engines are complex mechanisms with many different factors that influence their power and fuel efficiency. Because of the widespread use of the data, manufacturers want to insure they get the best possible results. To provide standardized information, the testing environment must be consistent for every test, day after day, year after year, or changes must be thoroughly investigated so that the appropriate adjustments in the results can be made. In both tests, these factors are called test conditions.

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[1] *OECD Standard Codes for the Official Testing of Agricultural Tractors*, Organisation for Economic Cooperation and Development, 1988. 2, rue Andre-Pascal, 75775 Paris CEDEX 16, France.

[2] Nebraska Tractor Test Laboratory, POB 830832, 134 Splinter Labs, UNL East Campus, Lincoln, NE 68583-0832.

Test conditions include the rules for the selection of the tractor and the control and/or recording of environmental conditions. During a PTO test, air temperature, barometric pressure, fuel type, fuel temperature, fuel measurement, lubricants, and accessory equipment on the tractor are recorded and monitored to ensure they are within acceptable limits. Strict control of these factors is important for two reasons. The tests measure the maximum power of the tractor and fuel efficiency; therefore, the testing conditions must be carefully controlled to insure accurate results. Each one of these factors will influence the power produced. The second reason is the desire to compare the test results of different tractors from different years.

For the drawbar test, all of the environmental factors in the PTO test must be accounted for, plus those that affect traction. The latter include tractor ballast, tires, and testing surface. The ballast, tires, and testing surface are critical because the amount of pull a tractor can produce at the drawbar is greatly influenced by the quality of the traction. Both the NTT station and the OECD station have strict standards on how all these factors are controlled and/or recorded.

In addition to the test conditions, the testing codes must establish rules governing such things as breakdowns, repeating tests, and testing accessory systems such as hydraulic systems, safety standards, noise standards, and the method of reporting and publishing the results.

7.6 Metric Problems

The following problems will demonstrate how to solve problems using ISO units.

Problem Determine the power being produced by a tractor if it developed 6.67 kN of force while traveling at a speed of 9.0 km/h.

Solution

$$\begin{aligned} P\ (\text{kw}) &= \frac{F\ (\text{kN}) \times V\ (\text{km/h})}{3.6} \\ &= \frac{6.67\ \text{kN} \times \ \ 9.0\ \text{km/h}}{3.6} \\ &= 16.675 \text{ or } 16.7\ \ \text{kW} \end{aligned}$$

Note: Appendix II includes conversions for customary and SI units. The answer to this problem could be converted to horsepower by using the appropriate conversion. Horsepower equals:

$$\text{Hp} = \frac{16.675\ \text{kW}}{0.7456999\ \dfrac{\text{kW}}{\text{hp}}} = 22.361 \ldots \text{ or } 22.36\ \text{hp}$$

Table 7.2 Direct conversions for derating factors

Accessories	10% other than fan and radiator 5% fan and radiator
Temperature	1% or each 5.6 °C above 29 °C for gasoline 1% for each 2.7 °C above 29 °C for diesel
Altitude	3% for each 305 m above 152 m
Type of service	10% for intermittent loads 20% continuous loads

Problem Determine the useable power for a 120 kW naturally aspirated, natural gas irrigation engine that will be operated with normal accessories, fan, and radiator. It is located at an elevation of 1000 meters and will operate in an air temperature of 38 °C and on continuous duty.

Solution The process is the same as customary units. The only difference is in the values used. For this example, direct conversions are used (Table 7.2).

The useable power is calculated by determining the total amount of power loss.

$$\text{Power loss } (\%) = L_{\text{acc}} + L_{\text{alt}} + L_{\text{temp}} + L_{\text{duty}}$$

$$L_{\text{acc}} = 10\% + 5\% = 15\%$$

$$L_{\text{alt}} = 3\% \times \left(\frac{1000\text{ m} - 152\text{ m}}{305\text{ m}}\right) = 3\% \times 2.78\ldots = 8.34\ldots\%$$

$$L_{\text{temp}} = 1\% \times \left(\frac{38 - 29}{4.72}\right) = 1\% \times 1.906\ldots = 1.906\ldots\%$$

$$L_{\text{duty}} = 20\%$$

$$\text{Total loss} = 15\% + 8.34\% + 1.906\% + 20\% = 45.246 \text{ or } 45\%$$

The useable tractor horsepower is 45% less than rated. Useable power is:

$$\text{Useable power} = 120\text{ kW} - \left(120\text{ kw} \times \frac{45\%}{100}\right) = 120\text{ kW} - 54 = 66\text{ kW}$$

All of the power losses for this engine are 54 kW, leaving 66 kW of useable power.

Chapter 8
Machinery Calibration

8.1 Objectives

1. Understand the need for evaluating the performance of machines.
2. Understand the principles of calibration.
3. Be able to calibrate a broadcast type fertilizer applicator.
4. Be able to calibrate a grain drill.
5. Be able to calibrate a row crop planter.
6. Be able to calibrate an air seeder.
7. Be able to calibrate a field sprayer.
8. Be able to prepare the proper mix of chemicals and water for a sprayer.

8.2 Introduction

One category of agricultural machines dispenses materials such as seeds, fertilizers, and chemicals. Dispensing machines are required to spread the material at a specific rate and in a specific pattern. Traditional dispensing machines dispensed the material at a fixed rate. These machines are still being used, but dispensing materials at a fixed rate does not meet the demands of modern agriculture. Modern machines are designed to dispense materials at a variable rate. This technology is one aspect of the new agricultural production method called precision agriculture. Dispensing machines used for precision agriculture production must not only be able to vary the application rate, but some machines must be able to vary the pattern also.

A machine that fails to dispense the material at the desired rate and in the desired pattern will waste resources and/or increase costs. If a seeder does not plant the correct amount of wheat seed, crop yield will be affected. If a sprayer applies more than the desired amount of material, desirable plants may be damaged.

The correct pattern is also important. The result of a sprayer with incorrect pattern will be streaks or skips. A grain drill can be planting the correct amount of seeds, but if the seeds are not dispensed uniformly, the yields can be affected.

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Evaluating the dispensing rate and pattern of dispensing for a machine is called calibration.

Historically calibration charts or tables came with dispensing machines. These publications would explain the adjustments or settings required to produce the desired dispensing rate and pattern. These publications are still available for many machines, but computers are taking over this job for many modern dispensing machines. For some machines the computer system may be limited to monitoring the machine performance, but some systems are capable of setting and or changing the application rate as the machine travels through the field. Even with computer system control, calibration is important to ensure the displayed rate is accurate.

The economic penalties and potential environmental damage from incorrect application of materials warrant the time and effort required to ensure the machine is dispensing the desired amount and that the distribution pattern is acceptable.

Checking a machine's application rate and dispersal pattern is called calibration. Although the exact procedure used to calibrate dispensing machines varies, this chapter will explain the calibration of four common agricultural material dispensing machines.

8.3 Principles of Calibration

The purpose of calibrating a dispensing machine is to ensure the machine is applying the desired amount of material and the material has the desired pattern of distribution. All dispensing machines should be calibrated periodically. The following sections will discuss some of the principles of calibration and provide example problems for calibrating several common agricultural machines.

8.3.1 Incorrect Application Rates and Patterns

Incorrect application rates and patterns have several causes. Five of these are:

1. The machine may have excessive wear.
2. The machine may have been damaged or modified incorrectly.
3. The machine may have been set incorrectly.
4. Variations in the weight, size, moisture content, and cleanliness of the material.
5. Variations in the physical condition (lumpiness, flowability) of the material being applied.

8.3.2 Acceptability

It would be a rare occurrence for a dispensing machine to distribute the desired exact amount of material. When perfection is not possible, levels of acceptability must be established. The amount of error that would be considered acceptable varies for each machine and situation. In some cases guidelines or standards have been established, but usually it is up to the owner/operator to determine the acceptable level of error. Standards of acceptability for each machine will be discussed in more detail for the four machines in the following sections.

8.3.3 Five Principles of Calibration

All methods used to calibrate agricultural machines are based on five principles: (1) Dispensing machines meter the flow (control the rate) of material at a predetermined rate selected by the operator. (2) The calibration procedure is completed by collecting material dispensed by the machine in units of volume, weight, mass, and number of granules or seeds per unit of area. (3) Machines can be calibrated using either stationary or mobile methods. (4) The calibration procedure must determine the representative area. (5) Calibration may include an evaluation of the distribution pattern. These five principles will be discussed in more detail in the following sections.

8.3.3.1 Material rate

Two different rate types are considered when calibrating machinery: flow rate and application rate. Flow rate refers to the volume or weight of material being dispensed over a unit of time. For sprayers, flow rate refers to the gallons per minute exiting the nozzles. In calibration of granular dispensing machines, flow rate usually means a volume or weight per unit area, for example, pounds per acre. This is known as application rate. Some machines, like row crop planters, can maintain an accurate application rate across a narrow range of speed because the flow rate of the material increases and decreases as the speed of travel increases and decreases. For others, like sprayers, the application rate is a function of the set flow rate and speed of travel.

During a calibration procedure for most machines, measuring devices must be capable of measuring fractional units, and care must be taken to ensure the material is collected and handled properly. The amount of time a machine is active during calibration is usually short. This can result in a small quantity of material; therefore care must be taken to ensure no material is lost and none is accidently added.

8.3.3.2 Calibration Units

Calibration methods measure material in units of volume, or weight, and compare the amount collected to an area. The unit of measure depends on the material being dispensed. When planting corn the desired rate is a specific number of seeds per acre or hectare. The application rate of sprayers is measured in gallons per acre or liters per hectare. Seeding rate of some grasses is in bushels per acre or liters per hectare. Lime is applied in tons per acre or metric tons per hectare. Even though the dispensing unit of area is usually acres or hectares, the unit of area used during calibration will be a representative sample because of the problems associated with collecting all of the material that would be dispensed for an acre or hectare.

8.3.3.3 Stationary vs. Mobile

Deciding between a stationary and mobile calibration is influenced by several factors. The two primary ones are the type of material being dispensed and how the flow of material is regulated. Most machines that dispense granular materials use a ground-driven metering unit. To calibrate these machines using the stationary method, the wheel that drives the metering unit is elevated off the ground, and it is turned for a calculated number of revolutions. This method would be acceptable for a granular fertilizer applicator but would not be acceptable for a manure spreader. For a mobile calibration of a granular dispensing machine, a container(s) is placed to capture the material flow, and the machine is driven for a calculated distance. This method is effective if just a few containers are required but becomes problematic if a large number of containers are needed. An alternative calibration method for granular dispensing machines is to weigh the machine, dispense the material for the calculated distance, and then reweigh the machine. This method is acceptable if the machine dispenses the correct or less than the desired amount, but if an excessive amount of material is applied, it cannot be removed.

For machines, such as sprayers, that have an engine-driven metering unit, a stationary calibration is completed by placing a container under each nozzle, and the sprayer is operated for a calculated amount of time. For a mobile calibration of a sprayer, containers are placed in the path of application, and the material is collected as the machine travels over the containers. The container area is used to determine the dispersal rate.

The advantage of the stationary method is that the machine can be calibrated in down time such as when the weather does not permit being out doors. The mobile method may work best when the machine has a large number of collection points. It is important to remember that the larger the area used, the better the results, but increasing the area collected during calibration increases the resources required to collect the material.

8.3.3.4 Representative Area

Dispensing machine calibration is accomplished by collecting an amount of material (volume or mass) and dividing it by the area covered. Two methods can be used to determine the representative area: (1) calculate the distance to travel or the number of turns of the drive wheel before starting to ensure the desired area is covered. (2) Turn the metering unit drive wheel a selected number of turns or travel a selected distance, and convert the results into the desired area using the width of the machine.

Calculating Area

For ground-driven metering units using stationary calibration, the number of turns required to cover the desired area is calculated first. During the calibration process, the metering unit drive wheel is turned a calculated number of revolutions. The number of turns depends on the width of the machine, the diameter of the wheel, and the size of the representative area. These principles are illustrated in the following sample problem.

Problem A lawn fertilizer spreader has a 16.0 inch diameter drive wheel and a dispensing width of 30.0 inches. The desire is to collect the spreader for 0.10 of an acre. How many turns of the drive wheel are required to cover 0.10 acres?

Solution The first step is to determine how far the machine will travel with each revolution of the wheel, the circumference of a circle. The circumference of a circle equation is used:

$$\text{Cir} = 2\pi \times r$$

where Cir = circumference, in; $\pi = 3.14$; r = radius, in
then:

$$\begin{aligned}\text{Cir} &= 2\pi \times r \\ &= 2 \times 3.14 \times \frac{16 \text{ in}}{2} \\ &= 50.24 \text{ in}\end{aligned}$$

The drive wheel will travel 50.24 inches with every revolution.

The next step is to determine how many revolutions will be required for the spreader to cover 0.10 acres. This will be determined using the unit cancellation method:

$$\begin{aligned}\text{Rev} &= \frac{1 \text{ Rev}}{50.25 \text{ in}} \times \frac{12 \text{ in}}{1 \text{ ft}} \times \frac{43{,}560 \text{ ft}^2}{\text{ac}} \times \frac{0.10 \text{ ac}}{} \times \frac{1}{30.0 \text{ in}} \times \frac{12 \text{ in}}{1 \text{ ft}} \\ &= \frac{627{,}264}{1507.5} \\ &= 416.09 \ldots \text{ or } 416 \text{ revolutions}\end{aligned}$$

The drive wheel would be turned 416 revolutions to represent the machine covering 0.10 acres.

Hand turning the wheel 416 revolutions may not be practical. If so, a smaller area should be used. Changing the area to 0.01 acres reduces the number of wheel revolutions to 41.6.

When a ground-driven metering unit is calibrated using the mobile method, the area is determined by calculating the distance the spreader must travel to cover the desired area. This will be explained by working a problem.

Problem What distance should be used for a mobile calibration of a spreader when the effective width of the broadcast pattern of the machine is 25.0 feet? The desired area is 0.10 acre.

Solution In this example area is determined by multiplying two distances, the distance traveled and the width of the distribution:

$$\text{Area} = \text{Distance}_\text{t} \times \text{Distance}_\text{w}$$

where Area = area, ac; Distance_t = travel distance, ft; Distance_w = distribution width, ft.

If the area and width of distribution are known, the equation can be rearranged to solve for the travel distance:

$$\text{Distance}_t = \frac{\text{Area}}{\text{Distance}_w}$$

$$D_t = \frac{A}{D_w}$$

$$= \frac{43{,}560 \text{ ft/ac} \times 0.10 \text{ ac}}{25.0 \text{ ft}}$$

$$= 172.24 \text{ or } 172 \text{ ft}$$

Material should be collected as the spreader travels 172 feet.

Converting Results

An alternative method for finding the representative area is to turn the drive wheel a selected number of turns, or travel a measured distance, and convert the results to the desired units. This method will also be explained using a problem.

Problem Determine the application rate for a machine, lb-/ac, that has a 40.0 inch diameter drive wheel and a dispensing width of 8.0 feet. Two and a half, 2.50, pounds of material were collected as the drive wheel was turned 25 revolutions.

Solution The first step is to determine the amount of material collected per revolution:

$$\frac{\text{lb}}{\text{rev}} = \frac{2.50 \text{ lb}}{25} = 0.100 \frac{\text{lb}}{\text{rev}}$$

One revolution of the wheel dispensed 0.1 pound of material.

The next step is to determine the area covered with one revolution of the drive wheel. Area covered per revolution is the circumference of the drive wheel times the width of the machine:

$$A = \text{Cir} \times \text{width}$$

$$= 2 \times \pi \times \frac{40.0 \text{ in}}{2} \times 8.0 \text{ ft} \times \frac{1 \text{ ft}}{12 \text{ in}}$$

$$= \frac{640}{24}$$

$$= 26.66\ldots \text{ft}^2$$

In one revolution of the drive wheel, the machine covered 26.66 square feet.

The last step is convert pounds per revolution and the area per revolution to pounds per acre. This will be accomplished using unit cancellation:

$$\frac{\text{lb}}{\text{ac}} = \frac{0.100 \text{ lb}}{\text{rev}} \times \frac{\text{rev}}{26.66\ldots \text{ft}^2} \times \frac{43{,}560 \text{ ft}^2}{\text{ac}} = \frac{4356}{26.66\ldots} = 163.35 \text{ or } 163 \frac{\text{lb}}{\text{ac}}$$

This machine is applying 163 pounds of material per acre.

Another conversion method is to collect the material as the machine travels a measured distance and convert the results to the desired units.

Problem Determine the application rate, gal/ac, for a machine that produced 2.34 ounces of liquid as the machine traveled 24.0 feet. The width of the machine is 36.0 inches.

Solution Several different approaches can be taken to solve this problem. For this example because the liquid collected was measured in ounces, the first step is determining the amount of liquid collected for the area covered, oz/ft^2:

$$\frac{\text{oz}}{\text{ft}^2} = \frac{2.34 \text{ oz}}{24.0 \text{ ft} \times 36 \text{ in} \times {}^{1 \text{ ft}}/_{12 \text{ in}}} = \frac{2.34}{72} = 0.0325 \ldots \text{ or } 0.0325 \frac{\text{oz}}{\text{ft}^2}$$

The machine dispensed 0.0325 ounces per square foot.

The next step is to convert ounces per square foot to gallons per acre:

$$\frac{\text{gal}}{\text{ac}} = \frac{0.0325 \text{ oz}}{\text{ft}^2} \times \frac{1 \text{ gal}}{128 \text{ oz}} \times \frac{43{,}560 \text{ ft}^2}{\text{ac}} = \frac{1415.7}{128} = 11.06 \ldots \text{ or } 11.1 \frac{\text{gal}}{\text{ac}}$$

The machine is applying 11.1 gallons per acre.

8.3.3.5 Distribution Pattern

For many dispensing machines, the function of the machine is to not only dispense the correct amount of material but to also dispense the material in a desired pattern. For example, row crop planters must place the seeds an equal distance apart. The desire for field sprayers is to spray the liquid in a uniform pattern. Methods for evaluating the distribution patterns of machines will be explained where appropriate in the following sections.

The following sections will explain the procedure for calibrating four agricultural dispensing machines.

8.4 Calibrating Fertilizer Applicators

Fertilizers are applied in liquid, gaseous, or granular form. The application of liquid fertilizers follows the same principles as spraying chemicals. Sprayers are discussed in a separate section. Gaseous fertilizers require specialized equipment and are very hazardous to use. The equipment to dispense gaseous fertilizers is not included in this text. The following section will discuss the calibration of granular fertilizer applicators.

Most granular fertilizer applicators will be one of two types, broadcast or gravity flow. A common agricultural broadcast spreader has a hopper to hold the material, a metering mechanism, and a spreading mechanism (Fig. 8.1).

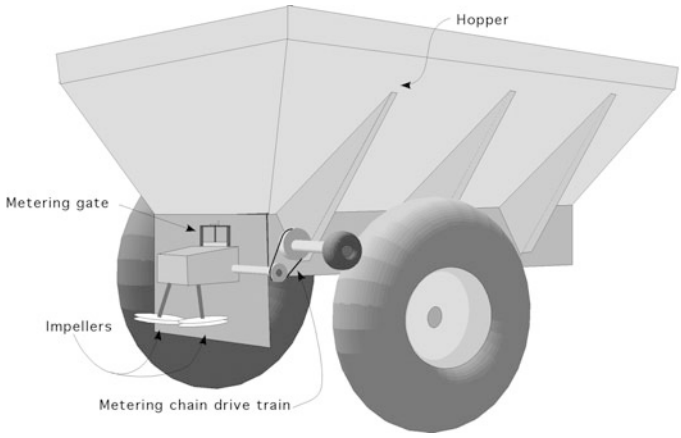

Fig. 8.1 Broadcast fertilizer spreader

Hoppers have tapered sides to feed the material to the conveyor chain that moves from front to back along the bottom of the hopper. Hopper capacities are usually measured in tons of fertilizer. Metering is usually accomplished by a variable speed conveyor chain in the bottom of the hopper and an adjustable opening at the back where the fertilizer drops onto the spreader(s). The chain auger is operated by a drive train powered by one of the wheels of the spreader. Because a ground wheel drives the chain auger, the amount of material dispensed changes as the speed of the spreader changes. The spreaders are usually powered by the tractor PTO and must turn at a constant speed for the spreader to have a consistent dispersal pattern. In this design the application rate of the material is set by changing the speed ratio of the drive train that powers the conveyor chain and/or changing the size of the opening at the metering gate. The process of using a variable opening for metering is called bulk metering. The material is spread as it drops onto one or more rotating disks, impellers, which propel it in a wide arcing pattern. Large spreaders have the impellers mounted on the back of the machine; smaller spreaders may have the impellers mounted in front of the hopper. A common horticultural design powers the impellers from the ground wheels, eliminating the need for a PTO or additional power source.

Gravity flow applicators also have a hopper, but the hopper extends across the width of the machine. The material is dispensed through adjustable openings along the bottom of the hopper. The rate of material flow is set by the size of the opening. This design uses an agitator along the bottom to prevent the material from bridging across the hopper and to break up lumps, thus improving the uniformity of flow. The material flow drops through the openings and onto the soil surface. Figure 8.2 shows a common horticultural gravity flow fertilizer applicator.

Gravity flow fertilizer spreaders were popular in agriculture, but problems associated with moving wide units on public roads have almost eliminated them for agricultural uses. Small ones are still used for lawn care and other situations where 18–24 inch widths can be effective.

Both types of spreaders can be calibrated using either the stationary or mobile method.

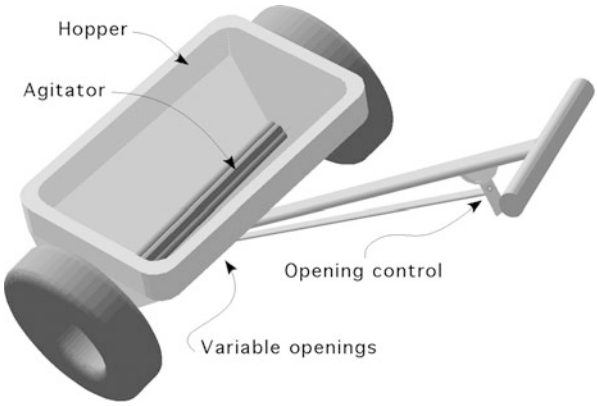

Fig. 8.2 Gravity fertilizer spreader

8.4.1 Gravity Flow Stationary Calibration

Stationary calibration is the preferred method for calibrating gravity flow fertilizer spreaders because the material flows out of the entire width of the machine. This makes it difficult to collect material from the spreader in a mobile calibration. During a stationary calibration, the material can be collected for a portion of the width, but the preferred method is to capture material from the entire width.

For a stationary calibration, the spreader must be secured so the drive wheel(s) are suspended and can be turned by hand. For the conversion method, the application rate, R, is determined by collecting the fertilizer for a selected number of turns of the metering drive wheel. The application rate is the pounds of material collected for the selected number of turns of the drive wheel divided by the area covered. The area covered is determined by multiplying the width of the spreader times the distance traveled. The distance traveled is determined by calculating the perimeter of the wheel ($2\pi r$) and multiplying it by the number of turns. The distance traveled is:

$$D = 2\pi r \times n$$

where D = distance covered, in; $2\pi r$ = circumference of circle, in; n = number of turns.

The area is:

$$A = w \times D$$

where A = area, in2; w = width of machine, in; D = distance traveled, in.

Note: because the standard unit of area is acres and the standard conversion from area to acres is feet squared. The area should be converted to square feet:

$$A\left(\text{ft}^2\right) = \text{in}^2 \times \frac{1\ \text{ft}^2}{144\ \text{in}^2}$$

Knowing the area in square feet and the weight of material collected, the application rate can be determined. In an equation this relationship is:

$$R = \frac{W}{A}$$

where R = application rate (lb/ft^2); W = weight of material (lb); A = area (ft^2).

The pounds per square foot is converted to the desired units of pounds per acre:

$$\frac{\text{lb}}{\text{ac}} = \frac{\text{lb}}{\text{ft}^2} \times \frac{43{,}560\ \text{ft}^2}{\text{ac}}$$

These multiple steps can be combined into one equation using a unit conversion. Entering this equation into a spreadsheet would reduce the computation time and the chance for errors when completing multiple calibrations. The equation is:

$$R = \frac{W}{0.0001442 \times r \times w \times n}$$

where R = application rate, lb/ac; W = material collected, lb; 0.0001442 = unit conversion; r = tire radius, ft; w = machine width, ft; n = number of turns.

Problem Determine the application rate for a 36.0 inch gravity flow fertilizer spreader. It has a 14.0 inch drive wheel, and 20 turns of the drive wheel produced 14.6 ounces of fertilizer.

Solution The previous equation will be used, but three of the values are not in the correct units. 36.0 inches = 3.0 feet, 14.0 inch diameter = 0.58 feet radius, and 14.6 ounces = 0.9125 lb.:

$$\begin{aligned} R &= \frac{W}{0.0001442 \times r \times w \times n} \\ &= \frac{0.9125}{0.0001442 \times 0.58 \times 3.0 \times 20} \\ &= \frac{0.9125}{0.00501816} \\ &= 181.839\ldots \text{or } 182\ \frac{\text{lb}}{\text{ac}} \end{aligned}$$

The gravity flow spreader applied 182 pounds per acre.

8.4.2 Broadcast Spreader Mobile Calibration

Mobile calibration may be difficult for large spreaders because of the width of the broadcast pattern and the volume of material that will be collected. On some machines the impellers can be disengaged and the fertilizer collected as it flows off the conveyor chain. The difficulty is insuring all of the fertilizer is collected.

Another method is to collect a sample area of the broadcast pattern. Both of these methods will be illustrated with a problem.

Problem You set your neighbor's broadcast spreader to apply 1200 lb/ac of fertilizer. During a mobile calibration, 160.0 pounds of fertilizer was collected as the drive wheel was turned 15 revolutions. The radius of the drive wheel is 21 in. The width of the broadcast was 30.0 feet. Is the application rate correct?

Solution

$$\begin{aligned} R &= \frac{W}{0.0001442 \times r \times w \times n} \\ &= \frac{160.0}{0.0001442 \times 1.75 \times 30 \times 15} \\ &= \frac{160.0}{0.1135575} \\ &= 1408.97\ldots \text{ or } 1410\ \frac{\text{lb}}{\text{ac}} \end{aligned}$$

The fertilizer spreader is applying 1410 pounds per acre of fertilizer.

In this problem the spreader is applying 210 pounds per acre more than the desired amount. Is this an acceptable level of accuracy? Should the spreader metering unit be adjusted and rechecked? No consistent standard has been established to determine the acceptable error for broadcast fertilizer spreaders. One way to evaluate the error is to calculate the percentage (%) of error. In this example the amount of error was 17.5% [(210 lb/1200 lb) × 100]. It would be up to the owner/operator to determine if 17.5% was an acceptable level of error.

The alternative method captures a sample of the broadcast area. Collectors (flat pans or pieces of plastic or tarp) of known area are randomly placed in the distribution path of the spreader or in a row perpendicular to the line of travel of the spreader. Note: care must be taken to insure the collection devices produce a representative sample. After the spreader is driven over the collectors, the material is weighed. The application rate (lb/ac) is computed by dividing the amount of material collected, by the area of the collectors, and then converting the answer to the desired units of volume weight or mass divide by the area. An advantage of the perpendicular row of collectors is that the distribution pattern can be evaluated by plotting the amount collected from each collector on a graph. This is explained in a later problem.

Problem What is the application rate of a spreader that deposited a total of 23.5 pounds of material on two tarps, each measuring 10.0 ft × 12.0 ft?

Solution:

$$\begin{aligned} R\left(\frac{\text{lb}}{\text{ac}}\right) &= \frac{W\,(\text{lb})}{A\ \ (\text{ac})} = \frac{23.5\text{ lb}}{2\text{ x }10.0\text{ ft} \times 12.0\text{ ft} \times \dfrac{1\text{ ac}}{43{,}560\text{ ft}^2}} = \frac{23.5}{0.005509\ldots} \\ &= 4265.25 \text{ or } 4260\ \frac{\text{lb}}{\text{ac}} \end{aligned}$$

[Note: this is an example where the number of significant figures in the answer could be ambiguous because of leaving a zero when rounding. To clarify the number of significant figures, the answer should be written as 4.26 E3.]

Problem Determine the application rate and distribution pattern for a broadcast spreader that was calibrated by placing 20–2 ft^2 collectors perpendicular to the direction of travel. The desired rate is 850 lb/ac. Table 8.1 shows the pounds of fertilizer collected.

Solution The first step is to determine the application rate by summing the quantity of fertilizer (W_t) in the 18 collector pans (n_c) containing fertilizer, Table 8.1:

$$W\,(\text{lb}) = 0.008 + 0.014 + 0.016 + 0.020 + 0.023 + 0.030 + 0.038 + 0.050 + 0.062 + 0.062 + 0.060 + 0.057 + 0.052 + 0.048 + 0.041 + 0.035 + 0.026 + 0.017 = 0.659\ \text{lb}$$

The next step is to determine the total area of the collector pans containing fertilizer:

$$A\left(\text{ft}^2\right) = 18 \times 2\ \text{ft}^2 = 36\ \text{ft}^2$$

Table 8.1 Fertilizer collected

Collector	lb
1	0.000
2	0.008
3	0.014
4	0.016
5	0.020
6	0.023
7	0.030
8	0.038
9	0.050
10	0.062
11	0.062
12	0.060
12	0.057
14	0.052
15	0.048
16	0.041
17	0.035
18	0.026
19	0.017
20	0.000

The application rate is:

$$R\left(\frac{\text{lb}}{\text{ac}}\right) = \frac{W_\text{t}}{A_\text{t}}$$
$$= \frac{0.659\ \text{lb}}{36\ \text{ft}^2 \times \dfrac{1\ \text{ac}}{43{,}560\ \text{ft}^2}}$$
$$= \frac{0.659}{8.264\ldots\text{E-4}} = 797.39 \text{ or } 800 \text{ or } 8.0\ \text{E2}\ \frac{\text{lb}}{\text{ac}}$$

The spreader is applying 800 pounds per acre. [Note: only 18 collectors were used to determine the area because two collectors did not have any measurable material.] In this case the percentage of error was:

$$\%(\text{error}) = \frac{850 - 800}{850} \times 100 = 5.88\%$$

This is an acceptable level of error. The calibration is completed by evaluating the distribution pattern. In this problem the collection pans were placed in a row perpendicular to the direction of travel. This provides the information that can be plotted on a graph. A plot of the distribution is shown in Fig. 8.3.

In the graph of the distribution, the dashed line represents the ideal or acceptable distribution for a broadcast fertilizer spreader with an overlapping pattern. The solid line is the distribution for this spreader. It is clear that this spreader has a problem. Even though the application rate is acceptable, the distribution of the material is not. This shape of pattern could result in streaking in the crop. The cause of the irregular distribution should be determined and corrected before the machine is used.

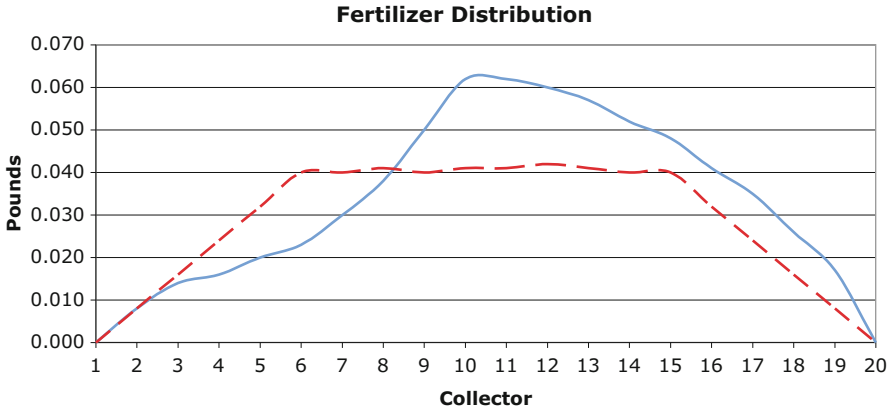

Fig. 8.3 Distribution graph for spreader

Another mobile method can be used if the spreader pattern is reasonably accurate. First, weigh the spreader, and then drive it over a measured area. Then reweigh the spreader. The difference between the before and after weights is the amount of material applied. The area is already known, so it is easy to find the application rate using the mobile calibration equation.

8.5 Calibrating Grain Drills

The traditional end wheel grain drill includes a hopper plus a metering unit, seed tube, and furrow opener for each row. They use a ground wheel and drive train to power the metering unit (Fig. 8.4). Grain drills use bulk or volume metering. The rows are usually spaced 6–10 inches (15–25 cm) apart. Combining the row spacing and number of metering units is the traditional method for indicating the width of the drill. A drill identified as 13–6 would have 13 metering units spaced 6 inches apart or a width of $(13 \times 6)/12 = 6.5$ feet.

The calibration of grain drills is more critical than the calibration of fertilizer spreaders because a small error in seeding rate can have a greater impact on the yield than an error in fertilizer application. In addition, it is more important that the seeds are planted uniformly. Grain drills can be calibrated stationary or mobile. The unit cancellation method can be used in either situation.

8.5.1 Grain Drill Stationary Calibration

End wheel grain drills drive half of the metering units from each wheel. For a stationary calibration, it is recommended to elevate one wheel at a time. A collection container is attached to each of the metering units driven by the elevated wheel. The drive wheel is turned a desired number of revolutions, if the area or conversion method is used. The process is repeated for the other drive wheel.

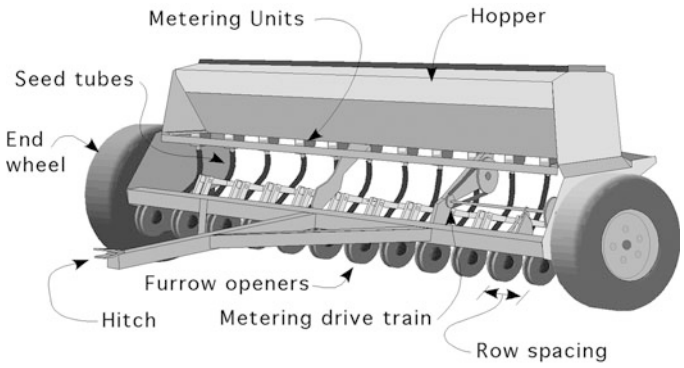

Fig. 8.4 End wheel grain drill

Table 8.2 Pounds of wheat collected from nine metering units

Unit	1	2	3	4	5	6	7	8	9
Lb	0.10	0.10	0.12	0.10	0.11	0.11	0.11	0.15	0.13

Problem An 18–6 (18 metering units spaced 6 inches apart) end wheel drill is set to apply 1.0 bu/ac of wheat. The quantity of seeds collected during calibration is shown in Table 8.2. The diameter of the drive wheel is 26.0 inches, and the drive wheel was turned 25 revolutions. Is the drill planting the correct amount of seed (bu/ac)? (Note: Because each wheel of an end wheel grain drill powers half of the metering units, only nine units are shown.)

Solution The first step is to determine the total weight of seed collected:

$$W_t = 0.10 + 0.10 + 0.12 + 0.10 + 0.11 + 0.11 + 0.11 + 0.15 + 0.13 = 1.03 \text{ lb}$$

The next step is to determine the bushels per acre. To complete this step, the problem can be broken down into several steps, or the unit cancellation method can be used. A previous section explained that calibration is determining a volume of material for an area. Using this concept, the drill can be calibrated by determining the volume (bu) and the area (ac).

It is common to measure wheat seeding rates in bushels per acre. In this example the wheat collected has the unit of pounds. A conversion from weight to volume is required. The relationship between weight and volume is the specific weight (γ) where:

$$\gamma = \frac{W}{V}$$

where γ = specific weight (weight/volume); W = weight (lb); V = volume (bu).

The standard specific weight of wheat is $\frac{60 \text{ lb}}{1 \text{ bu}}$. Therefore:

$$\text{Vol (bu)} = \frac{1.03 \text{ lb}}{60 \ \frac{\text{lb}}{\text{bu}}} = 0.0171667 \text{ bu}$$

The area is:

$$\begin{aligned} A \text{ (ac)} &= \frac{1 \text{ ac}}{43{,}560 \text{ ft}^2} \times \left(25 \text{ rev} \times \frac{\pi \times 26 \text{ in}}{\text{rev}} \times \frac{1 \text{ ft}}{12 \text{ in}} \right) \\ &\quad \times \left(9 \text{ unit} \times \frac{6.0 \text{ in}}{\text{unit}} \times \frac{1 \text{ ft}}{12 \text{ in}} \right) \\ &= \frac{110{,}214}{6{,}272{,}640} = 0.017570592 \text{ ac} \end{aligned}$$

The seeding rate in bushels per acre is:

$$R\left(\frac{\text{bu}}{\text{ac}}\right) = \frac{0.0171667\ \text{bu}}{0.017570592\ \text{ac}} = 0.977\ldots \text{or}\ 0.98\,\frac{\text{bu}}{\text{ac}}$$

The grain drill is planting 0.98 bushels of wheat per acre. The desired rate was 1.0 bushel per acre. Is the seeding rate acceptable? This is explained in the next section.

This is an example when perfection is not expected; therefore levels of acceptability must be established. Drill manufacturers may publish acceptable seeding rates for their products, or this information may be found in an extension bulletin. If these sources are not available, a standard has been established for grain drills. The seeding rate should be within plus or minus of 5% of the desired rate. When this method is used, acceptable limits are set on each side of the desired rate. If the actual rate falls within this limit, it is acceptable. In this example the upper limit (L_u) is:

$$L_\text{u} = 1.0 + (1.0 \times 0.05) = 1.05\,\frac{\text{bu}}{\text{ac}}$$

and the lower limit (L_l) is:

$$L_\text{l} = 1.0 - (1.0 \times 0.05) = 0.95\,\frac{\text{bu}}{\text{ac}}$$

Using this standard, the accuracy of the grain drill is acceptable ($1.05 > 0.98 > 0.95$).

In this example breaking the problem down into parts requires less math ability than trying to determine the answer by using one equation. The basic equation is relatively simple:

$$R\left(\frac{\text{bu}}{\text{ac}}\right) = \frac{\text{Vol (bu)}}{n_\text{r}\ \text{(rev)}} \times \frac{n_\text{r}\ \text{(rev)}}{A\ \text{(ac)}}$$

But when the values are included to arrive at bu/rev and rev/ac, the math is more complicated. The first variable for grain drills is determined by:

$$\frac{\text{Vol (bu)}}{n_\text{r}\ \text{(rev)}} = \frac{1\ \text{(bu)}}{\gamma\ \text{(lb)}} \times \frac{W\ \text{(lb)}}{n_\text{r}\ \text{(rev)}}$$

The second variable is determined by:

$$\frac{n_\text{r}\ \text{rev}}{A\ \text{(ac)}} = \frac{1\ \text{rev}}{\left(\pi \times \text{dia} \times \frac{1\ \text{ft}}{12\ \text{in}}\right) \times \left(n_\text{u}\ \times \frac{\text{width}}{\text{unit}} \times \frac{1\ \text{ft}}{12\ \text{in}}\right) \times \frac{1\ \text{ac}}{43{,}560\ \text{ft}^2}}$$

where n_u = number of metering units. Putting the two parts together produces:

$$R\left(\frac{\text{bu}}{\text{ac}}\right) = \frac{W\left(\text{lb collected}\right)}{\gamma\left(\frac{lb}{bu}\right) \times n_r\ (rev)} \times \frac{1 \text{ rev}}{\left(\pi \times \text{dia} \times \frac{1 \text{ ft}}{12 \text{ in}}\right) \times \left(n_u \times \frac{\text{width}}{\text{unit}} \times \frac{1 \text{ ft}}{12 \text{ in}}\right) \times \frac{1 \text{ ac}}{43{,}560 \text{ ft}^2}}$$

The solution for the sample problem is:

$$R\left(\frac{\text{bu}}{\text{ac}}\right) = \frac{1.03 \text{ lb}}{60\left(\frac{\text{lb}}{\text{bu}}\right) \times 25 \text{ rev}} \times \frac{1 \text{ rev}}{\left(\pi \times 26 \times \frac{1 \text{ ft}}{12 \text{ in}}\right) \times \left(9 \times \frac{6.0 \text{ in}}{\text{unit}} \times \frac{1 \text{ ft}}{12 \text{ in}}\right) \times \frac{1 \text{ ac}}{43{,}560 \text{ ft}^2}}$$

$$= \frac{0.000687 \text{ bu}}{\text{rev}} \times \frac{1 \text{ rev}}{0.000703 \text{ ac}} = 0.9767\ldots \text{ or } 0.98 \frac{\text{bu}}{\text{ac}}$$

The calibration of the drill is not completed until the uniformity of distribution is also checked. The acceptability of the distribution is determined setting upper and lower limits for each metering unit. The limits are set around the mean amount of seeds collected from the metering units. This will give:

$$\text{Mean} = \frac{W_t}{n_u} = \frac{1.03 \text{ lb}}{9 \text{ units}} = 0.1144\ldots \text{lb}$$

The distribution upper limit is:

$$\text{DL}_u = 0.114\ldots + (0.114\ldots \times 0.05) = 0.1197 \text{ or } 0.12 \frac{\text{bu}}{\text{ac}}$$

The distribution lower limit is:

$$\text{DL}_l = 0.114\ldots - (0.114\ldots \times 0.05) = 0.1083 \text{ or } 0.108 \frac{\text{bu}}{\text{ac}}$$

A comparison of these limits to the data shown in Table 8.2 indicates that although the grain drill seeding rate is acceptable, the distribution is not. The rate for metering units #8 and #9 is above the upper limit. Both metering units should be repaired before the drill is used.

8.5.2 Mobile Grain Drill Calibration

During a mobile calibration, collection containers are attached to each metering unit, and the drill is driven a measured distance. Mobile calibration is more

problematic than stationary because of the problem of attaching containers to the metering units that stay in place. The calibration process is the same as the one used for fertilizer spreaders—collecting the seeds and calculating the seeding rate.

Problem Determine the seeding rate for a 17–8 grain drill that traveled 50.0 feet during collection. 1.32 pounds of seeds were collected.

Solution

$$\begin{aligned}\frac{\text{bu}}{\text{ac}} &= \frac{1\text{ bu}}{60\text{ lb}} \times \frac{1.32\text{ lb}}{50.0\text{ ft}} \times \frac{43560\text{ ft}^2}{\text{ac}} \times \frac{1}{17 \times 8\text{ in }\times} \times \frac{12\text{ in}}{1\text{ ft}} \\ &= \frac{689{,}990.4}{40{,}8000} \\ &= 1.691\ldots \text{or } 1.69\,\frac{\text{bu}}{\text{ac}}\end{aligned}$$

The drill is planting 1.69 bushels per acre. In this example the distribution pattern cannot be checked because the data was not collected for each individual metering unit.

8.6 Calibrating Row Crop Planters

Row crop planters or precision planters are used to plant crops in rows while maintaining spacing between seeds within the row unlike those planted by grain drills. They use a different type of metering mechanism. Row crop planters are commonly used to plant large seeds, such as corn, soybeans, and sunflowers, but they are also used to plant small-seeded vegetable crops such as radishes. The common metering units for row crop planters are called plate, disk, and drum. A common feature of these types of metering units is that they adjust the planting rate for changes in velocity, within limits, using a mechanical drive wheel or computer controlled electric drive motor (Fig. 8.5).

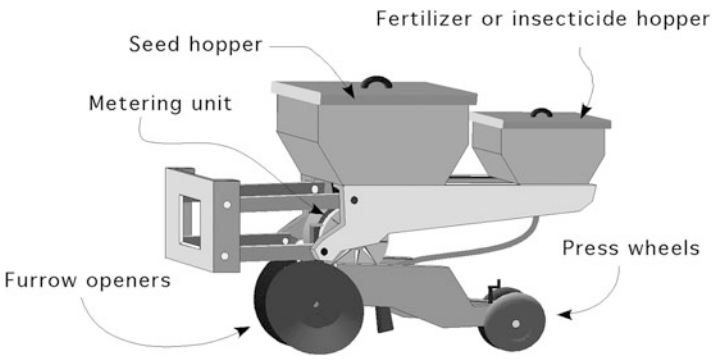

Fig. 8.5 Single unit of row crop planter

Plates are the tradition method for metering seeds, but for most crops, they have been replaced with disks. One style of antique plate planter was designed to plant hills of seeds, but most plate and the modern disk metering units singulate seeds. Singulating means selecting individual seeds from a volume of seeds. The plates are mounted horizontally underneath a seed hopper. The plates have cells, or notches, around the rim. As the plate rotates, the seeds are deposited in holes (cells) on the rim metering plate. As the metering plate rotates, the cells pass over a tube that connects to the furrow opener. The seeds drop from the plate and fall into the seed tube which delivers them to an open furrow in the soil. Two methods are used to change the seeding rate. A plate with a different number of cells can be used, and/or the drive train speed ratio between the drive wheel and the metering unit can be changed. Changing the speed ratio may require changing sprockets, but some planter designs use a gearbox for changing planting rate.

Disk metering units also have cells or holes in the rim, but the disk is mounted vertically. Different disks are used for different sizes of seeds and types of plants. They are called air planters because two different designs are used, based on air pressure either greater than or less than atmospheric. One type uses pressurized air to hold the seed in a vertical seed plate, and when the air is shut off, the seeds drop into the opened furrow or are blown into tubes that deliver them to the opened furrow. The other type of air planter uses a vacuum to hold the seeds in the cells in the seed plate. Both types of air planters change the seeding rate by changing disks and/or changing the speed ratio of the disk drive train.

The drum type of metering unit works on the same principles as the pressurized air disk planter. The primary difference is that the drum has a ring of holes for each row of plants instead of a separate metering unit for each row. Each drum usually singulates seeds for either 6 or 8 rows. The metering rate can be adjusted by changing drums and varying the speed between the drum and the drive wheel.

8.6.1 Row Crop Planter Stationary Calibration

Precision row crop planters can be calibrated using the stationary method. The seeding rate is calculated by dividing the seeds planted per revolution of the drive wheel by the representative acres covered per revolution of the drive wheel, or:

$$R = \frac{\frac{\text{sd}}{n_\text{r}}}{\frac{A}{n_\text{r}}}$$

This equation can also be written as:

$$R = \frac{\text{sd}}{n_\text{r}} \times \frac{n_\text{r}}{A}$$

where R = seeding rate (seeds/ac); sd = number of seeds; n_r = number of revolutions of drive wheel; A = area, ft^2.

Problem What is the planting rate for corn, seeds/ac, if 0.22 pounds of seed is weighed after an 18.0 inch drive wheel is turned 25 revolutions? The planter is set for 36.0 inch rows, and the seed size is 1500 seeds per pound.

Solution When calibrating row crop planters using the stationary method, the area used is determined by the row spacing and the representative distance traveled:

$$A = w \times d$$

where: $A = area\ (ft2)$; $w = row\ spacing\ (ft)$; $d = distance\ (ft)$.

The pounds per acre are:

$$\begin{aligned} R\left(\frac{\text{lb}}{\text{ac}}\right) &= \frac{W(\text{lb})}{n_{\text{r}}(\text{rev})} \times \frac{n_{\text{r}}(\text{rev})}{A(\text{ac})} \\ &= \frac{0.22\ \text{lb}}{25\ \text{rev}} \times \frac{1\ \text{rev}}{18.0\ \text{in} \times \frac{1\ \text{ft}}{12\ \text{in}} \times \pi \times \frac{1\ \text{ac}}{43{,}560\ \text{ft}^2} \times 36\ \text{in} \times \frac{1\ \text{ft}}{12\ \text{in}}} \\ &= \frac{0.22}{25} \times \frac{1}{3.245\ldots\text{E-4}} = \frac{0.22}{8.1136\ldots\text{E-3}} = 27.114\ldots\frac{\text{lb}}{\text{acre}} \end{aligned}$$

The planting rate in seeds per acre is:

$$R\left(\frac{\text{sd}}{\text{ac}}\right) = \frac{27.114\ldots\text{lb}}{\text{ac}} \times \frac{1500\ \text{sd}}{1\ \text{lb}} = 40{,}672.36 \text{ or } 40{,}700\ \frac{\text{sd}}{\text{ac}}$$

The row crop planter is planting 40,700 seeds per acre.

8.6.2 Row Crop Planter Mobile Calibration

Mobile calibration of precision row crop planters can be completed the same as fertilizer spreaders and grain drills, but because they place individual seeds in the ground a different method can also be used. For each row spacing and planting rate, there is a unique spacing for the seeds in the row. The planting rate of row crop planters can be determined by operating the planter in the field and measuring the seed spacing in the row.

To complete a mobile calibration of a row crop planter, seeds are added to the hopper, and the planter is lowered into the ground and driven for a short distance to ensure the system has stabilized. Next carefully uncover several seeds in a row and measure the distance between the seeds. On some models the press wheel can be disabled during this step to make seed spacing measurement easier. The average distance is used to determine the seeding rate.

Problem Determine the seeding rate, seeds/ac, for a row crop planter set for 20.0 inch rows. The in-the-row soybean spacing is 2–1/8, 2–1/4, 2–3/16, and 2–3/16 inches.

Solution First convert the fractional distances to decimals:

$$2\frac{1}{8} = 2.125$$

$$2\frac{1}{4} = 2.25$$

$$2\frac{3}{16} = 2.1875$$

Next determine the mean distance between the seeds in the row:

$$\text{Mean distance} = \frac{2.125 + 2.25 + 2.1875 + 2.1875}{4} = 2.1875 \text{ in}$$

The last step is determining the seeding rate:

$$R\left(\frac{\text{sd}}{\text{ac}}\right) = \frac{1 \text{ sd}}{2.1875 \text{ in}} \times \frac{12 \text{ in}}{1 \text{ ft}} \times \frac{43560 \text{ ft}^2}{1 \text{ ac}} \times \frac{1 \text{ row}}{20.0 \text{ in}} \times \frac{12 \text{ in}}{1 \text{ ft}}$$

$$= \frac{6{,}272{,}640}{43.75} = 143{,}374.62\ldots \text{ or } 143{,}000 \text{ or } 1.43 \text{ E5} \frac{\text{sd}}{\text{ac}}$$

This planter is placing 143,000 seeds per acre in the ground. To evaluate the acceptability of this performance, this rate must be compared to the desired rate.

If the operator of a row crop planter knows the in-the-row seed spacing for the seeds per acre and the row spacing, they can do a quick check of the planter performance by uncovering and measuring the distance between several seeds. This can be determined using the unit cancellation method.

Problem What should the in the row seed spacing (in/seed) be for 40,000 plants per acre when the planter is set for 28.0 inch rows?

Solution Using unit cancellation:

$$\frac{\text{in}}{\text{seed}} = \frac{1 \text{ ac}}{40{,}000 \text{ seed}} \times \frac{43{,}560 \text{ ft}^2}{1 \text{ ac}} \times \frac{144 \text{ in}^2}{1 \text{ ft}^2} \times \frac{1 \text{ row}}{28 \text{ in}}$$

$$= \frac{6{,}272{,}640}{1{,}120{,}000} = 5.60057\ldots \text{ or } 5.60 \frac{\text{row-in}}{\text{seed}}$$

Is this the correct answer? The units in the answer do not match the desired units. It is correct because it is common practice to drop off the unit of row in the answer and just use in/sd.

When doing a few calculations, it would be appropriate and preferred to complete the problem as in this example by using the unit cancellation method. This

would not be true if the in-the-row spacing needed to be calculated many times. In this situation it is easier to use an equation. In Chap. 1 the source of many equations was identified as unit cancellation calculations where the unit conversion numbers were reduced to a constant. Combining the unit conversion units in the previous problem (43,560 $ft^2 \times 144\ in^2$) produces the constant 6.273 E6. The seed spacing in the row can be found by the equation:

$$SS = \frac{6.273\ E6}{POP \times RS}$$

where SS = seed spacing in the row (in); POP = population, planting rate (seeds/ac); RS = row spacing (in).

If the seeding rate is not correct, further evaluation of the planter must be made. Because the metering unit is ground driven, the source of the error may be in the drive train ratio between the drive wheel and the metering unit.

This mobile calibration method is quick and requires very few resources. An additional benefit is that other planting parameters such as the seed depth and seed orientation can be evaluated at the same time.

8.7 Air Seeders

Air seeders have become the machine of choice for planting wheat and other crops in large fields. Seeders can have effective widths of 70–100 feet or more. The basic design is a combination of a seed cart containing a hopper and a bulk metering unit pulled behind a field cultivator or another secondary tillage machine that has soil-engaging tools mounted on shanks. The seed cart will have at least one but could have two or more hoppers. When multiple hoppers are used, one hopper will be for seed, and the other(s) can be used for fertilizer or other materials. Each hopper will have a single ground-driven metering unit that meters the material. Each metering unit controls the flow of material for all or a large number of soil-engaging tools. After metering the material passes through splitter manifolds until the stream is reduced down to volume for one opener (Fig. 8.6).

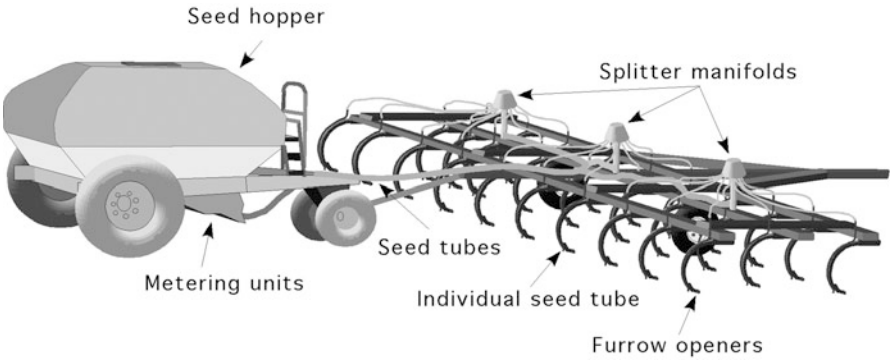

Fig. 8.6 Air seeder

Air seeder technology has progressed in recent years. Modern seeders combine the seed cart and soil-engaging tools into one unit. In addition the seed cart is placed in front of the soil-engaging shanks and in many machines, mounted on the back of the seed cart. The effectiveness of the soil opening devices and metering units has also been improved.

Most manufacturers state that air seeders can be calibrated using either stationary or mobile methods, but the size of these machines makes stationary calibration problematic. In addition the seeding rate for some air seeders calibrated stationary may be less than the actual rate in the field. For this reason the mobile calibration method is recommended.

8.7.1 Air Seeder Mobile Calibration

Mobile calibration methods for air seeders are the same as grain drills. One difference is the number of rows that must be collected. Air seeders have a large number of seed to soil interfaces, so collecting all of the seeds will require a lot of resources. Therefore it is common to collect a few of the rows and assume they are a representative sample. Recommendations for the number of rows that should be collected vary, but 25% is a general recommendation. It is important to collect the same number of points from each splitter manifold.

The appropriate number of seed hoses is disconnected from the individual seed tubes and connected to a bag or other collection device. The seeder is driven a fixed distance, 100–200 feet, and the material is weighed from each bag. With this information and the effective width of each shank, the seeding rate or application rate can be calculated.

Problem Determine the seeding rate (lb/ac) for a 50.0 foot air seeder with a 10.0 inch shank spacing. The following quantities of seeds were collected from every fourth shank on a single row during 200.0 feet of travel (Table 8.3).

Solution The first step is to determine the total amount of seeds collected:

$$\begin{aligned}\text{Total Pounds} &= 0.34 + 0.33 + 0.33 + 0.36 + 0.34 + 0.35 + 0.35 + 0.33 + 0.34 \\ &\quad +0.34 + 0.35 + 0.35 + 0.33 + 0.34 + 0.34 \\ &= 5.12 \text{ lb}\end{aligned}$$

The next step is to determine the area [Note: for calibration purposes the effective width is the number of shanks times the spacing between shanks.]:

$$\begin{aligned}\text{Area (ac)} &= \frac{10 \text{ in}}{\text{row}} \times \frac{1 \text{ ft}}{12 \text{ in}} \times 16 \text{ row} \times 200 \text{ ft} \times \frac{1 \text{ ac}}{43{,}560 \text{ ft}^2} \\ &= \frac{32{,}000}{522{,}720} = 0.06121\ldots \quad \text{or} \quad 0.061 \text{ ac}\end{aligned}$$

Table 8.3 Quantity of seeds collected during calibration of air seeder

Collector	lbs
1	0.34
2	0.33
3	0.33
4	0.36
5	0.34
6	0.35
7	0.35
8	0.33
9	0.33
10	0.34
11	0.34
12	0.35
13	0.35
14	0.33
15	0.34
16	0.34

The air seeder applied 5.45 pounds of seeds in 0.61 acre. The last step is to determine the pounds of seed per acre:

$$R\left(\frac{\text{lb}}{\text{ac}}\right) = \frac{5.12\ \text{lb}}{0.061\ \text{ac}} = 83.934\ldots \quad \text{or } 83.9\ \frac{\text{lb}}{\text{ac}}$$

The air seeder is applying seeds at the rate of 83.9 pounds per acre. It is up to the owner/operator to determine if this is an acceptable level of performance.

8.8 Calibrating Sprayers

Accurate calibration of spray equipment is very important because small variations in the application rate can cause chemical damage to the crop or the environment, be wasteful of materials or be ineffective. There are two important differences between the design of sprayers and that of grain drills, and row crop planters. (1) Sprayers do not use ground-driven metering units. The application rate (gal/ac) is a function of the flow rate of the nozzles (gal/min) and the velocity of the sprayer (mi/hr). The flow rate from the nozzles does not change when the ground speed changes; therefore changing the sprayer velocity changes the application rate. (2) Most agricultural sprayers use PTO or engine-driven pumps. To maintain a constant application rate, the PTO or engine speed must be constant. Ground driven pumps do exist, but they are not as common as PTO and engine driven pumps in dedicated spray equipment. The focus of this text will be on sprayers with PTO or engine equipped pumps.

The problems associated with variability in speed and flow can be managed by using a sprayer controller. Sprayer controllers are designed with a variety of capabilities. Simple controllers may just monitor system pressure and provide switches to operate the sprayer systems. The most expensive controllers will monitor and regulate all the sprayer systems. They have the ability to the vary application rate to compensate for changes in sprayer speed or changes in flow from the pump to insure the application rate is constant.

Figure 8.7 illustrates the common parts for the typical overlapping boom sprayer. Overlapping boom sprayers consists of tank, filter, pump, means to control the pressure, multiple boom sections with nozzles, and boom selection valve. The mixture in the tank flows through the filter to remove any particles that might plug the orifice in the nozzles and then to the pump. Several different types of pumps can be used, depending on the flow (gal/min) and the pressure (psi) needed by the system. From the pump the spray goes to the pressure-regulating valve. In some sprayer designs, a portion of the flow from the pump is returned to the tank for agitation. Fluid agitation is used to prevent the spray materials from separating in the tank. Mechanical agitation is used when fluid agitation will cause foaming of

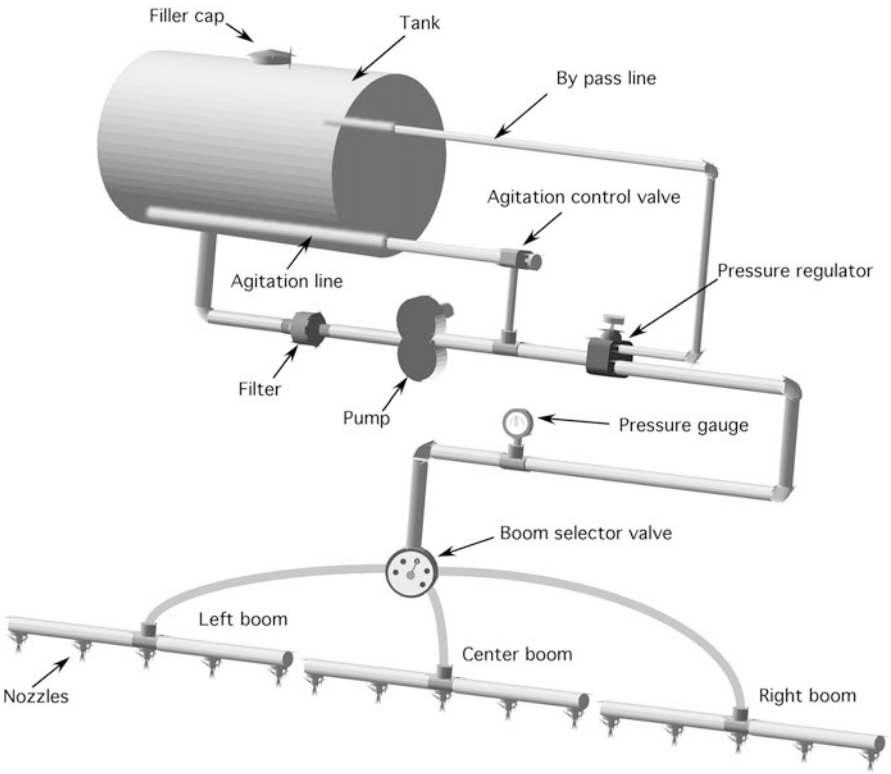

Fig. 8.7 Parts of a typical boom sprayer

the sprayer mix. Any excess flow produced by the pump is returned to the tank by the pressure-regulating valve. From the pressure-regulating valve, the fluid is pumped to the boom selector valve. At some point in this line, a connection is made for a pressure gage. The boom selector valve directs the flow of the mixture to the different sections of the boom. The boom selector valve can be manual, but some sprayer monitor systems control the boom sections electronically. Some sprayers have provisions for a handgun. A handgun is very useful for spraying skips or along fencerows and other obstructions.

One popular selector valve design has seven positions:

1. All outlets off
2. All booms on
3. Left boom on
4. Center boom on
5. Right boom on
6. Hand gun on
7. Booms and handgun on

In the typical design, the pump can be engine, power take off (pto), or hydraulic motor driven. As long as the pump is operating and the selector valve is in one of the on positions, fluid will flow. It is important to understand the effect ground speed has on the spray application rate (gal/ac). Unless the sprayer is equipped with monitoring system with variable flow rate capabilities, when it slows down, the application rate increases. This occurs because the nozzle flow rate (gal/min) is constant. When the travel speed is reduced, the same amount of material is applied to a smaller area:

$$\frac{\text{gal}}{\text{ac}} = \frac{\text{gal}}{\text{min}} \times \frac{\text{min}}{\text{ac}}$$

When the travel speed is reduced, the acres per minute (ac/min) are reduced. Conversely, when the sprayer travel speed increases, the application rate decreases. The effect of travel speed will become more apparent when reviewing the following problems, but changing the velocity by one mile per hour can change the application rate by several gallons per acre. For some materials this would cause serious consequences. Therefore, precise control of the sprayer speed is very important.

The design shown in Fig. 8.7 is often modified to meet the demands of different types of plants or application methods. Two additional examples are shown in Figs. 8.8 and 8.9.

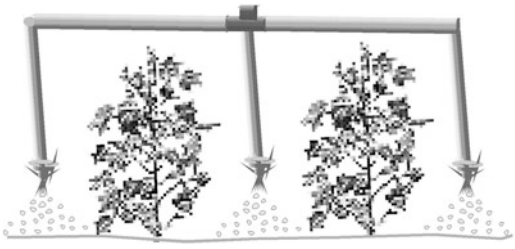

Fig. 8.8 Nozzles arranged for banding between the rows

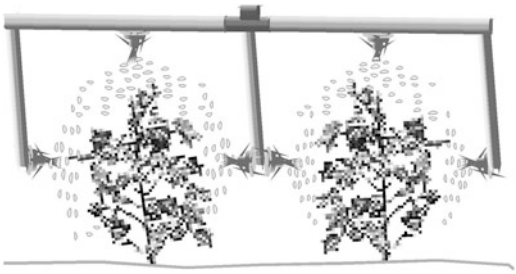

Fig. 8.9 Nozzles arranged for row crop sprayer

The application rate (gal/ac) of a field sprayer is controlled by three factors:

1. The speed of the sprayer (mi/hr)
2. The rate of discharge from the nozzle (gal/min)
3. The width covered by one nozzle (in.)

Sprayers can be calibrated using either the stationary or mobile method. During mobile calibration collectors are placed under each nozzle, and the sprayer is driven a calculated distance at the speed it will be operated in the field.

8.8.1 Sprayer Stationary Calibration

When the stationary method is used, collectors are placed under each nozzle, and the sprayer is operated for a specific time period. The specified time period can be preselected, or a recorded amount as long as it provides an adequate sample without exceeding the capacity of the collection vessel. The volume per time is converted to gallons per acre. The application rate can be calculated with the unit method or by an equation. The unit method:

$$\frac{\text{gal}}{\text{ac}} = \frac{\text{gal}}{\text{min}} \times \left[\frac{60\ \text{min}}{1\ \text{hr}}\right] \times \frac{1\ \text{hr}}{\text{mile}} \times \left[\frac{1\ \text{mile}}{5280\ \text{ft}}\right] \times \left[\frac{43{,}560\ \text{ft}^2}{\text{ac}}\right] \times \left[\frac{12\ \text{in}}{1\ \text{ft}}\right] \times \frac{\text{in}}{\text{noz}}$$

The bracketed variables are unit conversions. When they are combined, the source of the constant in the equation is evident:

$$\frac{60\ \text{min}}{1\ \text{hr}} \times \frac{1\ \text{mile}}{5280\ \text{ft}} \times \frac{43{,}560\ \text{ft}^2}{\text{ac}} \times \frac{12\ \text{in}}{1\ \text{ft}} = \frac{31{,}363{,}200}{5280} = 5940$$

The sprayer equation is:

$$R = \frac{5940 \times Q}{V \times w}$$

where R = application rate (gal/ac); 5940 = unit conversion constant; Q = flow rate per nozzle (gal/min); V = travel speed (mi/hr); w = nozzle spacing (in).

Note: Use either the flow rate (gal/min) from one nozzle and the spacing between two adjacent nozzles or the flow from all nozzles (gal/min × number of nozzles) and the total width of the sprayer (w × number of nozzle). In either case, the application rate (gal/ac) will be the same. Do not interchange these values.

Problem Determine the application rate for a sprayer that produced 0.14 gallons of spray in 1.12 min. The nozzle spacing is 18.0 inches and the travel speed was 4.3 miles per hour.

Solution

$$R = \frac{5940 \times Q}{V \times w}$$

$$= \frac{5940 \times \dfrac{0.14 \text{ gal}}{1.12 \text{ min}}}{\dfrac{4.3 \text{ mi}}{\text{hr}} \times 18 \text{ in}}$$

$$= \frac{742.5}{77.4} = 9.593 \ldots \text{ or } 9.6 \frac{\text{gal}}{\text{ac}}$$

This sprayer produced 9.6 gallons per acre of spray.

One of the methods used to adjust the application rate of a sprayer is changing the size (gal/min) of the nozzles. For this reason it is sometimes necessary to calculate the size of nozzle that should be used to apply the desired rate. The required nozzle size can be calculated by rearranging the equation to solve for nozzle size.

Problem What size of nozzles (gal/min) is required for a boom-type sprayer to apply 20.0 gallons of spray per acre? The sprayer has 24 nozzles spaced 18.0 inches apart.

Solution Because the application rate of field sprayers is speed-dependent, begin by selecting a reasonable speed that can be maintained in the field, and then determine the size of nozzles needed. For this problem we will use the typical speed (Appendix IV) of 6.5 mi/h. The required flow rate for the nozzles can be determined by rearranging the standard sprayer equation:

$$R\left(\frac{\text{gal}}{\text{ac}}\right) = \frac{5940 \times Q\left(\dfrac{\text{gal}}{\text{min}}\right)}{V\left(\dfrac{\text{mi}}{\text{hr}}\right) \times w \text{ (in)}}$$

$$Q\left(\frac{\text{gal}}{\text{min}}\right) = \frac{R \times V \times w}{5940} = \frac{\dfrac{20.0 \text{ gal}}{1 \text{ ac}} \times \dfrac{6.5 \text{ mi}}{\text{hr}} \times 18.0 \text{ in}}{5940}$$

$$= \frac{2340}{5940} = 0.3939 \ldots \text{ or } 0.39 \frac{\text{gal}}{\text{min}}$$

For this application rate and nozzle spacing, nozzles with a capacity of 0.39 gallons per minute would apply the desired 20 gallons per acre. The nozzles would be installed, and before the sprayer is used, it should be calibrated to ensure that the application rate is correct. New sprayer nozzles have small variations in the construction that can cause a sprayer to have an incorrect application rate. Small variation in the pressure at the nozzles can also cause an unacceptable error in the application rate.

Assume the operator installed the 0.39 gallon per minute nozzles on the sprayer and proceeded with the calibration.

Problem A container placed under all 24 nozzles of the sprayer collected 14.40 gallons of spray in 2.0 min of operation. The desired application rate was 20.0 gal/ac. Is the sprayer accurate?

Solution In this example only the total volume is known. One alternative is to determine the average flow rate per nozzle and then use the sprayer equation, but this process will not be as accurate as using the unit cancellation method and the total flow rate:

$$R\left(\frac{\text{gal}}{\text{ac}}\right) = \frac{14.40\ \text{gal}}{2.0\ \text{min}} \times \frac{60.0\ \text{min}}{1\ \text{h}} \times \frac{1\ \text{h}}{6.5\ \text{mi}} \times \frac{1\ \text{mi}}{5280\ \text{ft}} \times \frac{43{,}560\ \text{ft}^2}{1\ \text{ac}} \times \frac{12.0\ \text{in}}{1\ \text{ft}} \times \frac{1\ \text{nozzle}}{18.0\ \text{in}} \times \frac{1}{24\ \text{nozzles}} = \frac{451{,}630{,}080}{29{,}652{,}480} = 15.2307\ldots \text{or } 15\ \frac{\text{gal}}{\text{ac}}$$

The desired application rate was 20 gallons per acre, but the calibration indicates that the application rate is 5 gallons per acre less than this (20 gal/ac − 15 gal/ac). It is important to check the label of the chemical to determine if this is an acceptable application rate.

If the error is unacceptable, what should be done? The first step is to check the filters and nozzles of the sprayer to make sure that one or more are not slightly restricted. If all of the nozzles are in proper working order, the sprayer must be adjusted to apply the correct rate.

Adjustments can be made in the speed and/or the system pressure. To adjust the speed, the sprayer equation can be rearranged to calculate a new speed of travel. Adjusting the pressure is not as effective because adjusting the pressure can only make a small amount of change in the application rate. The pressure must be doubled to increase the flow rate by 50%, and modern boom-type sprayers operate within a narrow pressure range. For this problem we will adjust the speed of travel.

Unit cancellation could be used, but this example will rearrange the sprayer equation to solve for the speed of travel. The sprayer equation requires the flow rate per nozzle; therefore the average flow rate per nozzle must be determined. This average provides an acceptable level of accuracy:

$$\frac{Q}{\text{nozzle}} = \frac{\text{gal}}{\text{No.nozzle}} = \frac{14.4 \text{ gal}}{24 \text{ nozzles}} = 0.60 \frac{\text{gal}}{\text{nozzle}}$$

and because the spray was collected for 2 min:

$$Q \left(\frac{\frac{\text{gal}}{\text{min}}}{\text{nozzle}} \right) = \frac{0.60 \frac{\text{gal}}{\text{nozzle}}}{2.0 \text{ min}} = 0.30 \text{ gal/min/nozzle}$$

For convenience, the unit "nozzle" usually is not included; gpm = 0.30. Then:

$$R\left(\frac{\text{gal}}{\text{min}}\right) = \frac{5940 \times Q \left(\frac{\text{gal}}{\text{min}}\right)}{V\left(\frac{\text{mi}}{\text{hr}}\right) \times w \text{ (in)}}$$

$$V\left(\frac{\text{mi}}{\text{hr}}\right) = \frac{5940 \times Q\left(\frac{\text{gal}}{\text{min}}\right)}{R\left(\frac{\text{gal}}{\text{ac}}\right) \times w \text{ (in)}}$$

$$= \frac{5940 \times 0.30 \frac{\text{gal}}{1 \text{ min}}}{20.0 \frac{\text{gal}}{\text{ac}} \times 18 \text{ in}} = \frac{1782}{360} = 4.95 \text{ or } 5.0 \text{ mph}$$

If the speed of the sprayer is changed from 6.5 to 5.0 miles per hour, the sprayer will apply the correct rate.

Although the preferred way of calibrating a sprayer is to determine the nozzle size first, this method requires the purchase of a new set of nozzles if the correct size is not available. In some situations the nozzle size is selected first (the best available), and then the required speed of travel is determined. When this method is used, the calculated speed of travel may be unrealistic.

Problem The desire is to apply 15.0 gallons of spray per acre. The only nozzles available have a capacity of 0.25 gallon per minute. The sprayer has 35 nozzles spaced 24.0 inches apart. What speed will apply the correct rate?

Solution The sprayer equation could be rearranged to solve for speed. Instead this example will use the unit cancellation method:

$$V \left(\frac{\text{mi}}{\text{hr}}\right) = \frac{1 \text{ mi}}{5{,}280 \text{ ft}} \times \frac{43{,}560 \text{ ft}^2}{\text{ac}} \times \frac{1 \text{ ac}}{15.0 \text{ gal}} \times \frac{0.25 \frac{\text{gal}}{1 \text{ min}}}{\text{nozzle}} \times \frac{60 \text{ min}}{1 \text{ hr}} \times \frac{12 \text{ in}}{1 \text{ ft}} \times \frac{1}{24.0 \text{ in}}$$

$$= \frac{7{,}840{,}800}{1{,}900{,}800} = 4.125 \text{ or } 4.1 \frac{\text{mi}}{\text{hr}}$$

If the sprayer is operated at 4.1 miles per hour, the correct rate will be applied. This is slower than the typical velocity of 6.5 miles per hour. The owner/operator must decide if the sprayer is operated at 4.1 miles per hour, or a different set of nozzles are acquired.

8.8.2 Mobile Sprayer Calibration

To conduct a mobile sprayer calibration, the sprayer is set up ready to go to the field with collection containers under each nozzle. If the area method is used, the required distance is calculated before collecting any liquid from the sprayer. If the conversion method is used, a measured distance is marked out. The sprayer output is collected travelling the distance and the application rate is then calculated.

Problem Using the area method, determine the application rate for a boom row crop sprayer with 27 nozzles spaced 18.0 inches apart. The desire is to collect the sprayer for 0.10 acre.

Solution The first step is to determine the distance the sprayer must travel to cover 0.10 acres.

$$
\begin{aligned}
D\ (\text{ft}) &= \frac{43{,}560\ \text{ft}^2}{\text{ac}} \times \frac{12\ \text{in}}{1\ \text{ft}} \times \frac{1\ \text{noz}}{18.0\ \text{in}} \times \frac{1}{17\ \text{noz}} \\
&= \frac{522{,}720}{306} \\
&= 1708.23 \ldots \text{or } 1{,}710\ \text{ft}
\end{aligned}
$$

During calibration the sprayer should be driven 1710 feet.

Collecting the sprayer for 1710 feet produced 1.75 gallons of spray, Table 8.4.

Table 8.4 Sprayer calibration data

Nozzle	oz
1	11.78
2	11.65
3	11.78
4	12.80
5	12.80
6	14.08
7	14.08
8	14.08
9	14.08
10	14.08
11	11.65
12	11.78
13	11.78
14	14.08
15	14.08
16	15.36
17	14.08
	224.00

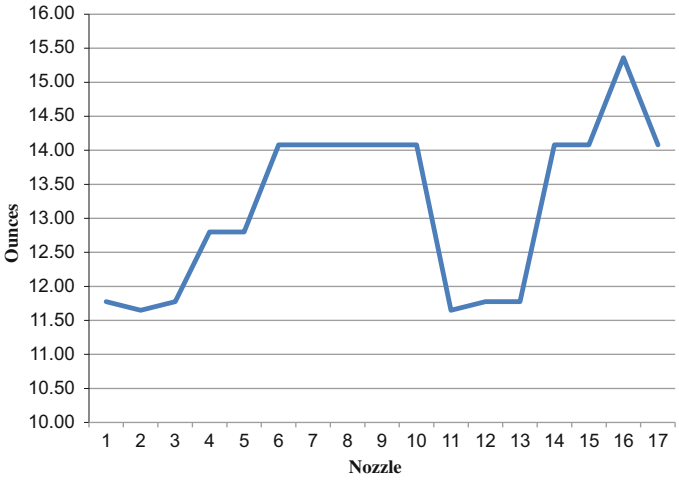

Fig. 8.10 Sprayer distribution

The application rate is:

$$R\left(\frac{\text{gal}}{\text{ac}}\right) = \frac{224\text{ oz}}{0.10\text{ ac}} \times \frac{1\text{ gal}}{128\text{ oz}} = 17.5\frac{\text{gal}}{\text{ac}}$$

The sprayer is applying 17.5 gallons per acre.

To fully calibrate the sprayer, the pattern should also be checked. Figure 8.10 is a chart of the sprayer distribution.

At first glance it would be easy to say that the sprayer has excessive variation in the output of the nozzles. A closer examination would show that the vertical scale is in ounces and that the variation from maximum to minimum is 3.71 ounces. Compared to the application rate of 17.5 gallons per acre, this is an error of 0.16 % (3.71/2240). The distribution is acceptable.

Other types of sprayers can be calibrated using these methods if the appropriate adjustments are made for differences in how the area and the application rate are determined. For example, to calibrate the row crop sprayer in Fig. 8.9, the width becomes the distance between the rows, and each nozzle should apply one-third of the required flow (gal/min) per row. Sprayers used for banding also can be calibrated. In checking a sprayer used for banding, the nozzle spacing (w) becomes the width of the band (Fig. 8.8).

8.9 Preparing Spray Mixes

A very important part of chemical application is the proper preparation and mixing of the chemical and the carrier (usually water). The application rates of most chemicals are given in terms of pounds of active ingredient per acre. The

concentration of a liquid chemical is usually printed on the label. A typical material might contain 4 pounds of active ingredient per gallon. Wettable powders (WP), on the other hand, are specified as a certain percent strength, such as a 50% or an 80% WP, which means that 50% or 80% of the weight of the material in the container is the active ingredient. The rest is inert material (carrier). Adding two pounds of a 50% wettable powder to ten gallons of water and applying the mixture to one acre would result in one pound of active ingredient per acre. To properly prepare sprayer mixes, a person must be able to determine the amount of chemical to add per gallon of water to achieve the desired rate of active ingredients per acre. Note: It is important to ensure the application rate of the active ingredient does not exceed the limits set by the label on the chemical container.

Problem Your desire is to apply 2.0 pounds of active ingredient of an 80% wettable powder in a 30.0 gallon per acre dilution. The sprayer has a 100.0 gallon tank. How many pounds of wettable powder are required to mix 100.0 gallons of spray?

Solution The first step is to determine the amount of wettable powder required to have 2.0 pounds of active ingredient:

$$\text{lb}_{\text{wp}} = \frac{2.0}{0.80} = 2.5$$

The application rate is 30.0 gallons per acre; therefore 2.5 pounds of wettable powder would be added to each 30 gallons of water.

The last step is determining how many pounds of powder to put in the tank. The tank holds 100 gallons or 3.33 units of 30 gallons. Because 2.5 pounds of wettable powder should be added to each 30 gallons of water, 3.33×2.5 or 8.33 pounds of wettable powder would be added to the tank.

The pounds of powder to be added to the tank can also be determined by setting up a ratio:

$$\frac{2.5 \text{ lb WP}}{30.0 \text{ gal } H_2O} = \frac{?\text{lb WP}}{100.0 \text{ gal } H_2O}$$

$$?\text{lb WP} = \frac{2.5 \times 100.0}{30.0} = 8.33 \ldots \text{ or } 8.33 \text{ lb } 80\%\text{WP}$$

8.33 pounds of 80 % wettable powder should be added to the 100.0 gallon tank.

Note: do not put the powder in the tank first, and do not add the powder to a full tank of water. Fill the tank about half full, add the powder, mix thoroughly, fill tank, and mix again. This mixture must be continuously agitated to prevent the wettable powder from settling.

Preparing a mix using liquid chemicals is accomplished with the same process.

Problem A liquid concentrate contains 2.0 pounds of active ingredient per 5.0 gallons. The desired rate is 1.0 pound of active ingredient per acre at a rate of 20.0

gallons of spray per acre. If the sprayer tank holds 180.0 gallons, how much water and how much concentrate should be used for each tank of spray?

Solution If the liquid contains 2.0 pounds of active ingredient per 5.0 gallons, then 2.5 gallons would contain 1.0 pound of active ingredient. Thus, for each acre 2.5 gallons of chemical is mixed with 17.5 gallons of water (2.0–2.5) to get 20 gallons of spray. By ratio:

$$\frac{2.5 \text{ gal concentrate}}{20.0 \text{ gal solution}} = \frac{?\text{gal concentrate}}{180.0 \text{ gal solution}}$$

$$?\text{gal concentrate} = \frac{2.5 \text{ gal concentrate} \times 180.0 \text{ gal solution}}{20.0 \text{ gal solution}} = 22.5 \text{ gal concentrate}$$

The tank holds 180 gallons, therefore 180 gallon − 22.5 gallon = 157.5 gallon. Thus, for every tank, 22.5 gallons of chemical is mixed with 157.5 gallons of water.

8.10 Metric Problems

Problem Determine the application rate (kg/ha) for a fertilizer spreader that applied 72.5 kg of material during 15 revolutions of the drive wheel, which has a diameter of 0.53 m. The effective width of the spreader is 0.76 m.

Solution

$$\begin{aligned} R\left(\frac{\text{kg}}{\text{ha}}\right) &= \frac{W(\text{kg})}{n_\text{r}(\text{rev})} \times \frac{n_\text{r}(\text{rev})}{A(\text{ha})} \\ &= \frac{72.5 \text{ kg}}{15 \text{ rev}} \times \frac{1 \text{ rev}}{p \times 0.53 \text{ m}} \times \frac{10{,}000 \text{ m}^2}{\text{ha}} \times \frac{1}{0.76 \text{ m}} \\ &= \frac{725{,}000}{18.98\ldots} = 38{,}195.079\ldots \text{ or } 38{,}000 \frac{\text{kg}}{\text{ha}} \text{ or } 38 \frac{\text{t}}{\text{ha}} \end{aligned}$$

Problem Determine the acceptability of the seeding rate for a grain drill when the desired rate is 90 kg/ha. The drill has 25 metering units with 0.20 m spacing. The drive wheel has an effective diameter of 80 cm. During the stationary calibration, the drive wheel was rotated 50 times. The following amounts of seeds were collected from 12 of the metering units (Table 8.5).

Table 8.5 Data for grain drill calibration in SI units

Unit	1	2	3	4	5	6	7	8	9	10	11	12
Grams	22.6	22.4	22.0	22.9	22.7	22.6	22.0	22.8	22.8	22.7	22.6	22.8

Solution The seeding rate is determined by calculating the quantity of seed for the representative area and then converting the results to the desired units.

The quantity collected is:

$$\begin{aligned}\text{Total} &= 22.6 + 22.4 + 22.0 + 22.9 + 22.7 + 22.6 + 22.0 + 22.8 + 22.8 \\ &\quad +22.7 + 22.6 + 22.8 \\ &= 270.9 \text{ g or } 0.2709 \text{ kg}\end{aligned}$$

The area is:

$$\begin{aligned}A \text{ (ha)} &= \text{No.Units} \times w(\text{m}) \times d(\text{cm}) \times \pi \times n_{\text{r}} \\ &= 12 \text{ units} \times 0.20 \frac{\text{m}}{\text{unit}} \times \frac{80 \text{ cm} \times \pi}{\text{rev}} \times 50 \text{ rev} \times \frac{1 \text{ m}}{1000 \text{ cm}} \times \frac{1 \text{ ha}}{10{,}000 \text{ m}^2} \\ &= \frac{30{,}159.28\ldots}{1.0 \text{ E7}} = 0.003015\ldots \text{ha}\end{aligned}$$

The seeding rate is:

$$R(\text{kg/ha}) = \frac{0.2709 \text{ kg}}{0.003015\ldots \text{ha}} = 89.822\ldots \text{ or } 89.8 \frac{\text{kg}}{\text{ha}}$$

The acceptability of the drill performance is determined by establishing the upper and lower limits using the 10% rule.

$$\begin{aligned}\text{Upper} &= 89.9 \times 1.05 = 94.3 \\ \text{Lower} &= 89.9 \times 0.95 = 85.3\end{aligned}$$

Based on the 10% rule, the performance of the grain drill is acceptable because $85.3 < 89.9 < 94.3$.

Even though the seeding rate is acceptable, the distribution pattern of the drill should also be checked:

$$\begin{aligned}\text{Mean} &= \frac{270.9 \text{ g}}{12} = 22.575 \text{ g} \\ \text{Upper limit} &= 22.575 \times 1.05 = 23.703\ldots \text{ or } 23.7 \text{ g} \\ \text{Lower limit} &= 22.575 \times 0.95 = 21.44\ldots \text{ or } 21.4 \text{ g}\end{aligned}$$

The distribution pattern is acceptable because all of the quantities for each metering unit are within the upper and lower limit.

Problem Determine the plants per hectare for a row crop planter when the average seed spacing is 11.5 cm in the row and the row spacing is 70 cm.

Solution

$$R\left(\frac{\text{Sd}}{\text{ha}}\right) = \frac{10{,}000\ \text{m}^2}{1\ \text{ha}} \times \frac{100\ \text{cm}}{\text{m}} \times \frac{1\ \text{sd}}{11.5\ \text{cm}} \times \frac{100\ \text{cm}}{\text{m}} \times \frac{1}{70\ \text{cm}}$$
$$= \frac{1.0\ \text{E8}}{805} = 124223.6025\ \text{ or }\ 124{,}000\ \text{ or } 1.24\ \text{E5}\ \frac{\text{sds}}{\text{ha}}$$

Problem Determine the seeding rate for a 10.8 m air seeder with 18 cm row spacing when 23 kg of seeds were collected during 50 m of travel.

Solution Since all of the rows were collected and the total width is known, the row spacing is not necessary:

$$R\left(\frac{\text{kg}}{\text{ha}}\right) = \frac{W\ \text{(kg)}}{A\ \text{(ha)}} = \frac{W\ \text{(kg)}}{\text{l (m) x } w\ \text{(m)}} \times \frac{10{,}000\ \text{m}^2}{\text{ha}}$$
$$= \frac{23\ \text{kg}}{50\ \text{m}} \times \frac{1}{10.8\ \text{m}} \times \frac{10{,}000\ \text{m}^2}{1\ \text{ha}}$$
$$= \frac{2.3\ \text{E5}}{540} = 425.925\ldots\ \text{ or }\ 426\ \frac{\text{kg}}{\text{ha}}$$

Problem Determine the size of nozzles (L/min) required to apply spray at the rate of 185 L/ha when the nozzle spacing is 0.4545 m and the sprayer will be traveling at a velocity of 4.0 km/hr.

Solution

$$Q\left(\frac{L}{\text{min}}\right) = 185\ \frac{L}{\text{ha}} \times \frac{1\ \text{ha}}{10{,}000\ \text{m}^2} \times 4\ \frac{\text{km}}{\text{h}} \times \frac{1\ \text{h}}{60\ \text{min}} \times \frac{1000\ \text{m}}{\text{km}} \times 0.45\ \text{m}$$
$$= \frac{3.33\ \text{E7}}{6.0\ \text{E7}} = 0.555\ \text{ or }\ 0.56\ \frac{L}{\text{min}}$$

Chapter 9
Equipment Efficiency and Capacity

9.1 Objectives

1. Be able to understand the concept of efficiency and be able to apply it to agricultural operations
2. Be able to understand the concept of capacity and be able to apply it to agricultural machines
3. Be able to calculate effective field capacity
4. Be able to calculate the throughput capacity of agricultural machines

9.2 Introduction

An efficient process is able to produce the desired results with a minimum of effort, resources, or waste. This is a concept that permeates our lives. A part of every occupation is the desire to improve the product or services by producing more for less or a better product for the same input. Engineers are constantly trying to improve the efficiency of operations by reducing the energy requirements and/or wastes from agricultural and manufacturing processes. When referring to machinery, efficiency is an evaluation of how well a machine does the tasks that it is designed to perform.

Capacity is a measurement of the amount of performance or machine capability. The evaluation of a machine's capacity is an important evaluation because underutilization of a machine increases the production costs and overutilization can lead to increased repair and maintenance costs. It can also shorten the life of a machine.

9.3 Efficiency

In this chapter the concept of efficiency will be used to evaluate how well a machine performs its designed task in terms of quantity and/or quality of performance. Owners and managers of farm enterprises are deeply concerned with efficient operation of equipment and other resources because inefficient operation leads to

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H.L. Field, J.M. Long, *Introduction to Agricultural Engineering Technology*,
https://doi.org/10.1007/978-3-319-69679-9_9

greater operating expenses and reduced profits. Efficiency is usually expressed as a percentage because efficiency is a ratio of two quantities having the same units, the unit cancel. A percentage is calculated by comparing to quantities and multiplying by 100.

Efficiency can be expressed mathematically in several forms. In the most general terms, efficiency can be expressed as:

$$\text{Efficiency } (E) = \frac{\text{output}}{\text{input}} \times 100$$

Efficiency is the ratio of what we get out of something relative to what we put in. If the output is 9 units (pounds, hours, etc.) and the input 10 units, the efficiency is:

$$\%\, E = \frac{\text{output}}{\text{input}} \times 100 = \frac{9}{10} \times 100 = 90\%$$

Or, if the output is 5 units and the input 10 units, the efficiency is:

$$\%\, E = \frac{\text{output}}{\text{input}} \times 100 = \frac{5}{10} \times 100 = 50\%$$

Efficiency can also be determined by comparing the actual performance to the theoretical performance. This equation is:

$$\%\, E = \frac{\text{actual}}{\text{theorectical}} \times 100$$

It is important to remember that an efficiency calculation provides a mathematical answer. The answer is only a tool or information that can be used to make a decision. For example, if you determine that the fuel efficiency of an automobile is 20 miles per gallon, that is not sufficient information to determine if the automobile is performing satisfactorily. This number must be compared to the historical performance, manufacturer's guidelines, or other data to make a decision on its acceptability.

Two additional examples of common uses of the term efficiency are internal combustion engines and electric motors. An internal combustion engine converts the chemical energy in fuel into power. Internal combustion engines are not 100% efficient because all the energy in fuel is not converted to power (the majority of the heat produced escapes through the radiator and out the exhaust). A typical gasoline engine is about 22% efficient; a diesel engine is 30–33%. An electric motor converts electrical energy into power with an efficiency of 95–98%.

The efficiency of engines, motors, mechanical powertrains and other mechanical devices can be determined if accurate numbers for the power in and power out can be determined.

9.3.1 *Performance Efficiency*

Performance efficiency refers to the quality of work done by a machine. The importance of a performance evaluation is not the same for all machines. For example, the quality of the job for primary tillage, like plowing, is not as critical to the profitability of the farming enterprise as the quality of the job for a combine. In addition, it would be very difficult to mathematically evaluate the quality of plowing.

For a harvesting machine, performance efficiency is a measure of the actual performance of the machine compared to the desired performance. For example, if the machine is a combine, the bushels of grain harvested would be measured and compared to the total bushels of standing grain in the field. Combines also could be evaluated according to the amount of damaged grain. Other harvesting machines could be evaluated on the basis of the amount of bruising of fruit or on the number of cracked shells.

A combine can lose grain in three different ways: the gathering unit can shatter grain from the head or drop heads, the threshing unit can fail to remove grain from the head as it passes through the machine, and the separating and cleaning unit can fail to separate the grain from the material other than grain (MOG). The losses are usually expressed as a percentage of the yield of the field.

Evaluating combine losses is a multiple-step problem. What we want to know is the amount of grain that the combine fails to put into the grain bin. The first step in evaluating the performance of a combine is to determine if a problem actually exists. This is accomplished by determining the total loss behind the machine.

To determine total loss, a known area is marked out, and the grain on the ground behind the combine is counted. Losses at this point include grain on the ground before the combine started (preharvest loss) and grain loss by the combine (machine loss). For most cereal grains, losses are determined by counting the number of grains in a known area, for example, 10 or 100 square feet. This will provide data with units of seeds per unit area. The table in Appendix III can be used to convert seeds per square feet (sds/ft^2) to bushels per acre (bu/ac) or seeds/m^2 to kilograms/ha.

Problem What is the performance efficiency (percent) in lost wheat for the combine shown in Fig. 9.1?

Solution Figure 9.1 represents the results of measuring the losses from a combine. The first step is to determine the total losses. In the example illustrated in Fig. 9.1, 162 seeds of wheat were counted in a 10 square foot area behind the machine.

From Appendix III, 20 seeds per square foot equals one bushel per acre. Applying the unit cancellation method:

$$\frac{\text{bu}}{\text{ac}} = \frac{162 \text{ seeds}}{10 \text{ ft}^2} \times \frac{1 \dfrac{\text{bu}}{\text{ac}}}{19 \dfrac{\text{seeds}}{\text{ft}^2}} = \frac{162}{190} = 0.8526 \text{ or } 0.85 \frac{\text{bu}}{\text{ac}}$$

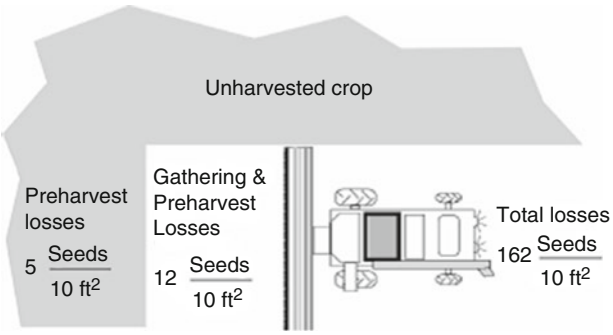

Fig. 9.1 Determining performance efficiency of a combine

Note The previous equation may be easier to understand by remembering that when dividing fractions, inverting and multiplying is the same operation. The previous equation can be written as:

$$\frac{\text{bu}}{\text{ac}} = \frac{162 \text{ seeds}}{10 \text{ ft}^2} \times 1\frac{\text{bu}}{\text{ac}} \times \frac{1 \text{ ft}^2}{19 \text{ seeds}}$$

Is a loss of 0.85 bu/ac an acceptable level of loss for this machine? As noted earlier, the mathematical calculations do not usually answer the question; they just provide information to make a more informed decision. The two common methods used to make informed decisions are to compare the results with the historical performance of the machine and to compare the results to an accepted standard. Research has shown that under favorable conditions, an expert combine operator should be able to keep losses to less than 1% but that losses up to 3% are typical. Therefore to determine the acceptability of the combine performance, the total losses must be compared to the standard. To determine the loss as a percentage, two values with the same units must be used. This is usually done with combines by comparing the loss and the crop yield (bu/ac) using the following equation:

$$L_t\% = \frac{L_t}{Y_t} \times 100$$

where $L_t\%$ = loss percent; Y_t = total yield; sd/ac, bu/ac, sd/m^2, or kg/ha; L_t = total loss; sd/ac, bu/ac, sd/m^2, or kg/ha.

For this example, we will assume that the wheat is yielding 30 bu/ac. The total loss percentage ($L_t\%$) is:

$$L_t\% = \frac{L_t}{Y_t} = \frac{0.85\frac{\text{bu}}{\text{ac}}}{30\frac{\text{bu}}{\text{ac}}} \times 100 = 2.833\ldots \text{ or } 2.8\%$$

Based on the less than 3% standard, this machine's performance would be considered acceptable. If the 1% standard was the desired performance level, the loss would be excessive, and additional calculations would be completed to determine the source(s) of the excessive grain loss.

At this point, it is important to remember that total loss is a combination of machine loss and preharvest loss. An unacceptable total loss does not necessarily mean there is a problem with the combine. The source of the unacceptable total loss may be preharvest losses. The combine has no influence on these losses. Preharvest loss is measured by counting the grain on the ground in the standing crop that has not been harvested. In Fig. 9.1, the preharvest losses are 5 seeds per 10 square feet. Therefore, the machine loss in bushels per 10 square feet is:

$$\begin{aligned}\text{Machine loss } (L_m) &= \text{total loss } (L_t) - \text{preharvest loss } \left(L_p\right)\\ &= \frac{162 \text{ sds}}{10 \text{ ft}^2} - \frac{5 \text{ sds}}{10 \text{ ft}^2}\\ &= 157 \frac{\text{sds}}{10 \text{ ft}^2}\end{aligned}$$

Converting this value to bushels per acre:

$$L_m = 157 \frac{\text{seeds}}{10 \text{ ft}^2} \times \frac{1 \dfrac{\text{bu}}{\text{ac}}}{19 \dfrac{\text{seeds}}{1 \text{ ft}^2}} = \frac{157}{190} = 0.826\ldots \frac{\text{bu}}{\text{ac}}$$

Converting this to a percent:

$$L_m = \frac{0.83 \dfrac{\text{bu}}{\text{ac}}}{30 \dfrac{\text{bu}}{\text{ac}}} \times 100 = 2.754\ldots \text{ or } 2.8\%$$

Rounding to two significant figures, the total loss and machine loss are both 2.8%. The preharvest loss is too small of a percentage to be measured.

It can now be concluded that, if the 1% standard is used, the losses are excessive, and the machine is the source of the excessive losses. When this occurs, it is necessary to determine which component of the machine is the source of the losses.

The first step is to check the gathering unit. The performance of the gathering unit (header) is checked by backing the combine a distance less than the length of the machine and counting the seeds on the ground between the header and the uncut crop. Figure 9.1 shows that the losses in this area are 12 seeds per 10.0 square feet. (Remember that this also includes the preharvest losses.) The gathering unit (L_g) losses are determined by subtracting the preharvest loss from seeds counted in the area between the header and the uncut crop.

$$L_g = \frac{12 \text{ seeds}}{10.0 \text{ ft}^2} - \frac{5 \text{ seeds}}{10.0 \text{ ft}^2} = \frac{7 \text{ seeds}}{10 \text{ ft}^2} = 0.7 \frac{\text{seeds}}{\text{ft}^2}$$

Converting this value to bushels per acre:

$$\frac{\text{bu}}{\text{ac}} = 0.7\frac{\text{seeds}}{\text{ft}^2} \times \frac{1\dfrac{\text{bu}}{\text{ac}}}{19\dfrac{\text{seeds}}{\text{ft}^2}} = \frac{0.7}{19} = 0.0368 \text{ or } 0.04\frac{\text{bu}}{\text{ac}}$$

or as a percent:

$$\frac{0.04\dfrac{\text{bu}}{\text{ac}}}{30\dfrac{\text{bu}}{\text{ac}}} \times 100 = 0.13\%$$

This shows that the gathering unit losses are 0.13%, a very small part of the total machine losses.

When neither the preharvest loss nor the gathering unit losses are excessive, the threshing and separating units must be checked.

Threshing losses are represented by heads or cobs on the ground behind the machine with grain still attached. Cleaning and separating losses are represented by grain on the ground behind the machine that is not preharvest or gathering unit loss. Cleaning and separating losses can be determined by subtraction:

$$L_{\text{c\&s}} = L_{\text{t}} - L_{\text{p}} - L_{\text{g}} - L_{\text{th}}$$

where $L_{\text{c\&s}}$ = cleaning and separating losses; L_{t} = total losses; L_{p} = preharvest losses; L_{g} = gathering unit losses; L_{th} = threshing losses.

$$\begin{aligned} L_{\text{c\&s}} &= L_{\text{t}} - L_{\text{p}} - L_{\text{g}} - L_{\text{th}} \\ &= 162\frac{\text{sds}}{10\ \text{ft}^2} - 5\frac{\text{sds}}{10\ \text{ft}^2} - 7\frac{\text{sds}}{10\ \text{ft}^2} - 0\frac{\text{sds}}{10\ \text{ft}^2} \\ &= 150\frac{\text{sds}}{10\ \text{ft}^2} \end{aligned}$$

Note that the threshing losses are listed as zero. This is because the information is not available to determine this loss. The threshing and separating loss percentage is:

$$\frac{\text{bu}}{\text{ac}} = \frac{150\ \text{sds}}{10\ \text{ft}^2} \times 1\frac{\text{bu}}{\text{ac}} \times \frac{1\ \text{ft}^2}{19\ \text{sds}} = \frac{150}{190} = 0.789\ldots \text{ or } 0.79\frac{\text{bu}}{\text{ac}}$$

$$\% = \frac{0.79\dfrac{\text{bu}}{\text{ac}}}{30\dfrac{\text{bu}}{\text{ac}}} \times 100 = 2.631\ldots \text{or } 2.6\%$$

Clearly, if the desire is to improve the performance of the combine, the cleaning and separating units should be adjusted or repaired.

9.3.2 Field Efficiency

Field efficiency is usually used to evaluate the performance of tillage or harvesting machines. It is a comparison of the actual amount of "work" (volume of activity, not Force × Distance) done by a machine compared to what it would do with no lost time or capacity. The maximum rate that a machine can perform is determined by the width of the machine and the speed of travel. When a machine operates with a constant width and travels at a constant speed, it will perform at 100% field efficiency. A machine is capable of operating at 100% field efficiency for short periods of time, but as soon as the speed changes (slow down for turns, terraces, etc.) or the width changes (overlap width of the machine to prevent skips), the efficiency drops below 100%. The primary cause of loss efficiency is lost time (unproductive time) and a working width of the machine less than the maximum. Typical field efficiencies for common machines can be found in Appendix IV. This concept is illustrated in more detail in the next section, on capacity.

9.4 Capacity

The term capacity is used to evaluate the productivity of a machine. In agriculture, two types of capacity are commonly used, *field capacity* and *throughput capacity*. Field capacity is used to evaluate the productivity of machines used to work the soil, such as plows, cultivators, and other machines such as drills, sprayers, and harvesting machines. Throughput capacity is a measure of the volume of material that passes through a machine, machines such as grain augers, balers, forage harvesters, and combines.

An additional concept relating to both types of capacity is the difference between theoretical and actual productivity. If a tillage machine operates at 100% efficiency, it is operating at 100% capacity. This is called the *theoretical field capacity*. Theoretical field capacity is determined using the width of the machine and the speed of travel. It can be calculated using unit cancellation, but an equation is also available.

$$\text{Theoretical field capacity } (C_T) = \frac{S \times w}{8.25}$$

where C_T = theoretical field capacity, ac/hr; S = speed of travel, mi/hr; w = width of the machine, ft; 8.25 = units conversion constant, 43,560 ft^2/ac ÷ 5280 ft/mi.

This equation can be used as long as the unit used for speed is miles per hour and the unit used for the width of the machine is feet.

Problem Determine the theoretical capacity for a machine that travels at 5.0 mph and has an operating width of 20.0 ft.

Solution

$$C_T = \frac{S \times w}{8.25} = \frac{5.0\,\frac{\text{mi}}{\text{hr}} \times 20.0\text{ ft}}{8.25} = 12.12\ldots \text{ or } 12\,\frac{\text{ac}}{\text{hr}}$$

If this machine travels at a constant speed and uses a constant width, it has a theoretical capacity of 12 ac/h.

Effective field capacity is the amount of productivity that actually occurred not what is theoretical possible. The difference between theoretical capacity and effective capacity is lost capacity. Lost capacity is an important concern for the machine operator and/or manager because it represents lost revenues or resources. There are two primary causes of lost capacity, lost time, time not operating, and operating the machine with less than the maximum working width. Common causes of lost time include:

1. Mechanical breakdowns
2. Taking time to adjust the machine
3. Stopping to fill seed hoppers, spray tanks, etc.
4. Slowing down to turn at the end of the row or crossing waterways, etc.
5. Operator rest stops

It is not uncommon for machines to be operated at less than maximum width. For example, when tilling with a disc or field cultivator, it is a common practice to overlap each pass to insure there are no skips. Overlapping each round reduces the effective width of the machine.

The equation for effective capacity is the same as theoretical capacity with a field efficiency added. A range of typical field efficiency values for common machines can be found in Appendix IV. The common equation for effective field capacity is:

$$C_E = \frac{S \times w \times E_f}{8.25}$$

where C_E = effective field capacity, ac/hr; S = average speed of travel, mph; w = effective width of the machine, ft; E_f = field efficiency, decimal form.

Problem Assume that the operator in the previous problem averages 0.75 hr of lost time per 10.0 hr day. What is the effective field capacity?

Solution The first step is to determine the time efficiency:

$$E_f = \frac{\text{output}}{\text{input}} \times 100 = \frac{10.0\text{ hr} - 0.75\text{ hr}}{10.0\text{ hr}} = 92.5\%$$

The second step is to determine the effective capacity:

$$C_E = \frac{S \times w \times E_f}{8.25} = \frac{5.0\text{ mph} \times 20.0\text{ ft} \times 0.925}{8.25} = \frac{95.5}{8.25} = 11.21\ldots \text{ or } 11\ \frac{\text{ac}}{\text{hr}}$$

The effect of lost productivity is apparent. The theoretical capacity is 12 ac/hr, but because of lost time, the effective capacity is 11 ac/hr.

The concept of effective capacity also can be used to determine the amount of time it would take a machine to cover a field.

Problem How many hours will it take to cultivate 200.0 acres with a field cultivator that is 24.0 ft wide?

Solution This is an example of a problem with a hidden intermediate step. Before the hours can be determined, the effective capacity of the machine must be calculated. *Note*: the effective capacity equation requires three values. Two of these, speed and field efficiency, are not given in the problem. If the actual speed and the field efficiency are unknown, the typical values found in Appendix IV can be used. In Appendix IV, the typical field efficiency for a field cultivator is 85%, and the typical speed is 5.5 mph. With these values, the effective capacity can be calculated:

$$C_{\mathrm{E}} = \frac{S \times w \times E_{\mathrm{f}}}{8.25} = \frac{5.5 \ \frac{\mathrm{mi}}{\mathrm{hr}} \times 24.0 \ \mathrm{ft}\acute{}0.85}{8.25} = \frac{112.2}{8.25} = 13.6 \text{ or } 14 \ \frac{\mathrm{ac}}{\mathrm{hr}}$$

Once the effective capacity is known, the time required to work the field can be calculated. Using unit cancellation:

$$\text{hour} = \frac{1 \ \mathrm{hr}}{14 \ \mathrm{ac}} \times 200 \ \mathrm{ac} = 14.28 \ldots \text{or } 14 \ \mathrm{hr}$$

If the average field speed is 5.5 mph and the operator can maintain a field efficiency of 85%, it will take 14 hr to cultivate the 200 acre field.

9.5 Throughput

The concepts of theoretical and effective capacity also are applicable to throughput capacity. Throughput incorporates time, but because throughput usually refers to the flow of material through a machine, the units may be different from those used for capacity. For example, the performance of a hay baler could be evaluated using units of bales per hour or tons per hour.

Problem What is the throughput capacity of a baler that baled 150.0 tons in 1 week while operating an average of 6.0 hr per day?

Solution The units of the throughput capacity are not identified. They could be tons/week, tons/day, or bales/day. For this example, assume that the manufacturer advertises that the baler has a capacity of 6 tons/hr and the owner wants to compare the actual performance to the advertised performance. This means the effective throughput capacity needs to be calculated in units of ton/hr.

$$\frac{\mathrm{ton}}{\mathrm{hr}} = \frac{150.0 \ \mathrm{ton}}{\mathrm{week}} \times \frac{1 \ \mathrm{week}}{5 \ \mathrm{day}} \times \frac{1 \ \mathrm{day}}{6.0 \ \mathrm{hr}} = \frac{150}{30} = 5.0 \ \frac{\mathrm{ton}}{\mathrm{hr}}$$

Knowing the actual throughput for the baler, the throughput efficiency can be determined. The throughput efficiency is:

$$E = \frac{\text{output}}{\text{input}} \times 100 = \frac{5.0 \dfrac{\text{ton}}{\text{hr}}}{6.0 \dfrac{\text{ton}}{\text{hr}}} \times 100 = 83.3\ldots \text{ or } 83\%$$

Assuming the advertised throughput of the baler is a reasonable value, this operation is only 83% efficient in baling hay.

The throughput of a baler also can be evaluated in units of bales per hour (bales/hr). To use these units, additional information is required, including the weight of the hay (lb/bale) and two unit conversion values.

Problem Determine the effective throughput in units of bales per hour if each bale weighs 1200.0 lb.

Solution No equation has been presented to solve this problem. This is an example where unit cancellation can be used.

$$\begin{aligned}\frac{\text{bales}}{\text{hr}} &= \frac{150.0\ \text{ton}}{\text{week}} \times \frac{1\ \text{week}}{30\ \text{hr}} \times \frac{2000\ \text{lb}}{1\ \text{ton}} \times \frac{1\ \text{bale}}{1200.0\ \text{lb}} \\ &= \frac{3.0\ \text{E5}}{3.6\ \text{E4}} = 8.333\ldots \text{ or } 8.33\ \frac{\text{bales}}{\text{hr}}\end{aligned}$$

These examples show that throughput can be expressed in many different ways depending on the values being compared. Remember that efficiency is a ratio—both values must have the same units. In addition, these examples illustrate the usefulness of unit cancellation for solving problems of this type.

9.6 Metric Problems

Problem Determine the theoretical capacity for a 20.0 m wide cultivator traveling at 9.6 km/hr.

Solution

$$\begin{aligned}C_T\left(\frac{\text{ha}}{\text{hr}}\right) &= S\left(\frac{\text{km}}{\text{hr}}\right) \times w(\text{m}) \times \frac{1000\ \text{m}}{\text{km}} \times \frac{1\ \text{ha}}{10{,}000\ \text{m}^2} \\ &= 9.6 \frac{\text{km}}{\text{hr}} \times 20.0\ \text{m} \times \frac{1000\ \text{m}}{\text{km}} \times \frac{1\ \text{ha}}{10{,}000\ \text{m}^2} \\ &= \frac{192{,}000}{10{,}000} = 19.2 \frac{\text{ha}}{\text{hr}}\end{aligned}$$

Problem What is the effective capacity for the cultivator in the previous problems if the operator wasted 0.75 hr per 10.0 hr working day?

Solution The first step is to solve for the time efficiency.

$$\begin{aligned}\text{Efficiency } (\%) &= \frac{\text{output}}{\text{input}} \times 100 \\ &= \frac{10.0 \text{ hr} - 0.75 \text{ hr}}{10.0 \text{ hr}} \times 100 = \frac{9.25}{10.0} \times 100 = 92.5\%\end{aligned}$$

The effective capacity is:

$$\begin{aligned}C_{\mathrm{E}}\left(\frac{\text{ha}}{\text{hr}}\right) &= S\left(\frac{\text{km}}{\text{hr}}\right) \times w(\text{m}) \times \frac{1000 \text{ m}}{\text{km}} \times \frac{1 \text{ ha}}{10{,}000 \text{ m}^2} \times E_{\mathrm{F}} \\ &= 9.6 \frac{\text{km}}{\text{hr}} \times 20.0 \text{ m} \times \frac{1000 \text{ m}}{\text{km}} \times \frac{1 \text{ ha}}{10{,}000 \text{ m}^2} \times 0.925 \\ &= \frac{177{,}600}{10{,}000} = 17.8 \frac{\text{ha}}{\text{hr}}\end{aligned}$$

Problem How many hours will it take to cultivate 20.0 ha with an 8.0 m cultivator traveling at 10 km/hr? Assume a field efficiency of 85%.

Solution The first step is to determine the effective field capacity.

$$\begin{aligned}C_{\mathrm{E}}\left(\frac{\text{ha}}{\text{hr}}\right) &= \mathrm{S}\left(\frac{\text{km}}{\text{hr}}\right) \times w(\text{m}) \times \frac{1000 \text{ m}}{\text{km}} \times \frac{1 \text{ ha}}{10{,}000 \text{ m}^2} \times E_{\mathrm{F}} \\ &= 10 \frac{\text{km}}{\text{hr}} \times 8.0 \text{ m} \times \frac{1000 \text{ m}}{\text{km}} \times \frac{1 \text{ ha}}{10{,}000 \text{ m}^2} \times 0.85 \\ &= \frac{68{,}000}{10{,}000} = 6.8 \frac{\text{ha}}{\text{hr}}\end{aligned}$$

The second step is to calculate the amount of time it will take to cultivate 20.0 ha with a field capacity of 6.8 ha/hr.

$$\text{Time (hr)} = \frac{1 \text{ hr}}{6.8 \text{ ha}} \times 20.0 \text{ ha} = 0.3095 \ldots \text{ or } 2.9 \text{ hr}$$

Chapter 10
Economics of Agricultural Machinery

10.1 Objectives

1. Be able to list the criteria for selecting tractors and machines
2. Be able to determine optimum machine size
3. Be able to calculate ownership and operating costs of agricultural equipment
4. Understand ways to reduce the costs of owning and operating tractors and machinery
5. Understand the concept of break-even use (BEU) for a machine
6. Be able to calculate BEU for a machine
7. Understand the importance of regular maintenance of agricultural machinery

10.2 Introduction

Machinery is one of the largest investments for agricultural enterprises beyond the land intself. The selection process includes decisions on manufacturer, design, size, and options. A bad decision on any one of these factors could have a detrimental effect on the usability of the machine. After studying this chapter, you should have a better understanding of the criteria to use when selecting tractors and machines and be able to match tractor and machine sizes.

10.3 Selection Criteria

Some of the characteristics or capabilities of a machine that make one more attractive than another are easily determined, but others are more abstract. It is easy to understand that the number of shanks and shank spacing on a field cultivator is an important consideration. The type of points or shovels on the shanks determines the soil action. These characteristics can have a tremendous bearing on the quality of the machine and/or the quality of its performance. The following sections will discuss some of the criteria that should be used when selecting a tractor or machine and illustrate their importance.

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10.3.1 Company Name

Manufacturers spend years and multitudes of resources establishing their reputation. A company's reputation is based on the quality and durability of its products and service to its customers. All machines will require parts at some point in their life and skilled technicians to install them.

The importance of selecting tractors and machinery from reputable companies cannot be overstated. A case could be made that the best economic decision would be to choose one tractor or machine over another, even though it did not have the better durability record, just because the reputation of the manufacturer was better.

An important factor to consider on brand name is the availability of parts. A low-cost tractor or machine that has an extended downtime each time it needs a part is not a good investment.

10.3.2 Cost

Cost is always an important consideration when purchasing any item. It is important to remember that the lowest priced tractor or machine may not be the least expensive when both ownership and operating expenses are considered. The lowest priced machine may have the lowest ownership costs, but the operating costs may offset this advantage. *Note*: these costs are explained in a later section.

An important aspect of the ownership cost of a machine is the downtime. Whenever a machine is not available because of the need for repairs, the cost to the enterprise is not just the cost of the repairs; it also includes lost capacity or lost time. When the crop is ready for harvest and the combine is not available because it needs repairs, there is a cost associated with leaving the crop in the field after it is ready for harvest, because some of the crop could be lost.

10.3.3 Repairs

All machines have breakdowns, but the quality of the construction will dramatically influence the repair costs for a tractor or machine. There is also a correlation between the complexity of a tractor or machine and the cost of repairs. It would be expected that a combine would have more repair costs than a cultivator. The cost of repairs is also influenced by the use and abuse of the tractor or machine. Any equipment that is not maintained or used in a manner not recommended by the manufacturer will have greater repair costs. As discussed in the previous section, downtime for repairs is also important because of the lost capacity. Evaluate equipment not only on its quality and durability but also on the amount of time and money that will be required to have it repaired.

10.3.4 Design

The design of the machine is an important consideration. All balers produce bails of forage, and they can look very similar, but they can have many differences in the

working components. Small variations in design may make one more suitable than the others for a given situation. For most tillage equipment, the cost of the machine is primarily determined by the quantity of the steel it contains. A tillage machine designed for use in fields that are large and relatively flat will have wide rigid sections. But a machine that is designed for terraced or undulating fields will require a frame with more flexibility. More flexibility will require a more complicated frame that will cost more money. A rigid frame cultivator used in a terraced field will not produce satisfactory results and will have greater repair costs. It can be difficult to know what features of a design improve the value of a machine for a particular situation without an understanding of the advantages and disadvantages of the different designs.

10.3.5 Capacity

The trend in agriculture has been to larger farms. This trend has increased the demand for machines with larger and larger capacity. A previous chapter discussed that the options for increasing capacity are using a wider width, operating at a faster speed (both requiring more power), and increasing efficiency of operation.

It also is important to be able to complete the operation in a timely fashion. Unfortunately, information on the timeliness of agricultural operations is limited. Some concepts of timeliness and the effect of machine size are discussed in the next section.

10.4 The Optimum Machine Size

Optimizing the machine size is one technique for reducing production costs. When the machine is too small, the operating costs may be higher, and its reduced capacity will require a greater number of hours to complete an operation. It is also possible to exceed the design forces when the machine size is small for the available power. When the machine is too large, power is the limiting factor, and the machine may not produce the desired results, or the life of the tractor may be shortened, because modern tractors are designed to operate at lighter drafts and faster speeds.

The optimum machine size can be selected from two different points of view: it can be based on the amount of time available to complete an operation, or it can be based on the amount of power available from the tractor. The process used depends on the situation.

10.4.1 Time Limitation

When the limiting factor is time, the first step is to determine the amount of available time to complete the operation and then determine the size of machine required. Once the machine size is determined, the required tractor size can be determined. If timeliness is the highest priority, the calculation may show that a

larger tractor will be required. A full discussion of timeliness is beyond the scope of this text, but we will illustrate this concept for determining the size of machine and tractors.

Problem A general recommendation is that the primary tillage for planting corn should not take longer than 1 week. If you anticipate planting 500 acres of corn and only work 12.0 hr per day and 6 days per week, what size of moldboard plow do you need if you can plow at typical speed and efficiency?

Solution The first step is to determine the capacity of the plow, C_E (ac/hr) required to plow the ground in the available time. This can be accomplished by using unit cancellation:

$$C_E\left(\frac{\text{ac}}{\text{hr}}\right) = \frac{500\ \text{ac}}{1\ \text{wk}} \times \frac{1\ \text{day}}{12.0\ \text{hr}} \times \frac{1\ \text{wk}}{6\ \text{day}} = 6.944\ldots \text{or } 6.9\ \frac{\text{ac}}{\text{hr}}$$

To plow 500 acres in 1 week, the plow must have a width and be operated at a speed that will produce a capacity of 6.9 ac/hr. The second step is to determine the width of the plow. This is accomplished by remembering that the capacity of field equipment can be determined by using the effective capacity equation (Chap. 9):

$$C_E = \frac{V \times w \times E_f}{8.25}$$

Rearranging this equation to solve for width (w) and looking up the typical speed and efficiency in Appendix IV results in the width of the plow:

$$w = \frac{C_E \times 8.25}{V' E_f} = \frac{6.90\frac{\text{ac}}{\text{hr}} \times 8.25}{4.5\frac{\text{mi}}{\text{hr}} \times 0.80} = \frac{56.925}{3.6} = 15.8125 \text{ or } 16\ \text{ft}$$

To be able to plow the field in 1 week, assuming that the plow will be operated at typical speed and efficiency, will require a plow with an effective width of 16 ft. Plows are not usually sized by feet of width; instead they are sized by the effective width of each plow bottom and the number of bottoms. Sixteen feet is the same as a 12–16 plow (12 bottoms with 16 inches per bottom).

The next step is to determine the size of the tractor needed to pull the plow. This is accomplished by determining the drawbar horsepower required. The first step is to replace the term force in the drawbar power equation with the term draft (D_F) or draft force.

$$P_{DbHP} = \frac{D_F \times V}{375}$$

The term draft is used to describe the amount of force required to pull a machine. Appendix V gives the American Society of Agricultural and Biological Engineers (ASABE) standard values for the draft of agricultural machines. Notice that more than one type of unit is used for draft. That is, the draft of plows is listed as pounds of force per square inch (cross sectional area) plus a speed factor, spring tooth harrows are listed as pounds per foot of width, and some rotary power machines are

given in horsepower. It is important to pay close attention to the units being used so that the equation can be modified to match the machine. The draft is calculated by the following equation:

$$D_F = F_i \times \left[C_1 + (C_2 \times V) + \left(C_3 \times V^2\right)\right] \times w \times T_d$$

where D_F = draft, lb or N; F_i = soil texture factor. For fine soils $i = 1$, for mediums soils $i = 2$, and for coarse textured soils $i = 3$; C_1, C_2, C_3 = machine specific parameters from Appendix V; w = machine width, ft or m; T_d = tillage depth, in. or cm.

Problem What size of tractor (Dbhp) will be required to pull the 12–16 (16.0 ft) plow that was calculated in the previous problem?

Solution The first step is to find the draft of the plow in Appendix V. Notice that the draft for a plow varies with soil type. We will assume that the plow will be used in a clay soil, which is a fine textured soil.

From Appendix V, for customary units, we find the following parameters:

$$\begin{aligned} F_i &= 1.0 \\ C_1 &= 113 \\ C_2 &= 0 \\ C_3 &= 2.3. \end{aligned}$$

The tillage depth is $T_d = 6$ in., and the plow width is $w = 16$ ft.

Selecting a depth of 6.00 inches and solving for draft:

$$\begin{aligned} D_F &= F_i \times \left[C_1 + (C_2 \times V) + \left(C_3 \times V^2\right)\right] \times w \times T_d \\ &= 1.0 \times \left[113 + (0 \times 4.5) + \left(2.3 \times 4.5^2\right)\right] \times 12 \text{ bottoms} \times \frac{16 \text{ in}}{\text{bottom}} \times \frac{1 \text{ ft}}{12 \text{ in}} \times 6.0 \text{ in} \\ &= \frac{183{,}830.4}{12} \\ &= 15{,}319.2 \text{ or } 15{,}000 \text{ lb} \end{aligned}$$

Solve for drawbar power in hp:

$$\begin{aligned} P_{\text{DbHP}} &= \frac{D_F \times V}{375} \\ &= \frac{15{,}000 \times 4.5}{375} \\ &= 180.0 \text{ or } 180 \text{ hp} \end{aligned}$$

With typical speed and efficiency and operating 6 inches deep in clay soil, the 12–16 plow will require a tractor with 180 drawbar horsepower.

One result of using this method to determine the optimum size of machines is now apparent. The calculated tractor size may be larger than the size of tractor that you have. What are your alternatives if you do not want to purchase a larger tractor? Plowing is usually the highest draft tillage operation on a farm, so a tractor could be leased for the time required to do the plowing. The plowing could be hired out. Another option, which might allow you to complete the plowing with the tractor

available, is to adjust one or more of the factors in the drawbar horsepower equation. A common practice is to extend the amount of time available to complete the tillage operation. It also is possible to reduce the draft of the plow by reducing the operating depth or to reduce the speed. In some situations, one of these two choices is the best option, but for this problem, the available time will be adjusted.

10.4.2 Power Limitation

When the limiting factor is power, the recommended procedure is to determine the maximum size of the machine that can be powered by the tractor. When power is the limiting factor, the calculations may result in a time requirement for completion of the activity that is not realistic.

Problem Assume that the largest tractor you have available to pull a plow is 100 drawbar horsepower. If this tractor is used, how many 12 hr days will it take to plow 500 acres?

Solution The first step is to determine the size of plow the 100 Dbhp tractor can pull. This is accomplished by rearranging the drawbar horsepower equation to solve for width [because Area (A) = Width(w) × Depth (d)]:

$$W\,(\text{in}) = \frac{\text{Dbhp} \times 375}{D \times d \times s} = \frac{100.0\ \text{Dbhp} \times 375}{\frac{14.0\ \text{lb}}{\text{in}^2} \times \frac{6\ \text{in}}{1} \times \frac{4.50\ \text{mi}}{1\ \text{hr}}}$$
$$= \frac{37{,}500}{378} = 99.206\ldots \text{or } 99.2\ \text{in}$$

Under the conditions set up in this problem, the 100.0 Dbhp tractor is capable of pulling a plow that is 99.2 inches wide. A 99.2 inch-wide plow would be 6.2 or 6, 16 inch bottoms. Therefore, a 6–16 plow (8.00 ft) is used.

The next step is to determine the capacity of a plow 8.00 ft wide:

$$C_{\text{E}} = \frac{S \times W \times E_{\text{f}}}{8.25} = \frac{4.50\frac{\text{mi}}{\text{hr}} \times 8.00\ \text{ft} \times 0.80}{8.25} = \frac{28.8}{8.25} = 3.4909\ \ldots\ \text{or}\ 3.5\ \frac{\text{ac}}{\text{hr}}$$

Determining the number of days using unit cancellation:

$$\text{days} = \frac{1\ \text{day}}{12\ \text{hr}} \times \frac{1\ \text{hr}}{3.5\ \text{ac}} \times 500\ \text{ac} = 11.9047\ldots \text{or } 11.9\ \text{days}$$

This means using the 100 Dbhp instead of the 180 Dbhp will take 6 extra days (12 days – 6 days = 6 days) to plow the field.

10.4.3 Matching Tractors and Machines

Studies have shown that many agricultural producers operate with tractors that are capable of pulling much larger equipment. This increases the production costs. This problem is common after purchasing a new tractor because new tractors are usually larger than the one being replaced. Whenever a producer purchases a new tractor, they should ensure the machines are matched to the power available. The process is explained in the following problem.

Problem The opportunity to buy a 185 PTO horsepower tractor is too good to pass up. What size (width) of offset disk harrow (W_{dh}) and field cultivator (W_{fc}) will you need for your new tractor? The disc harrow is operated 6 inch deep. Assume a clay soil and the lowest typical value for speed and efficiency. *Note*: remember to convert from PTO power to drawbar power using the 86% rule.

Solution To solve this problem, PTO power must be changed to drawbar power:

$$P_{\mathrm{DbHP}} = \mathrm{PTO}_{\mathrm{HP}} \times 0.86 = 185\ \mathrm{hp} \times 0.86 = 159\ \mathrm{hp}$$

Draft can be calculated by rearranging the drawbar power equation:

$$\begin{aligned} P_{\mathrm{Dbhp}} &= \frac{V \times D_{\mathrm{F}}}{375} \\ D_{\mathrm{F}} &= \frac{P_{\mathrm{DbHP}} \times 375}{V} \\ &= \frac{159\ \mathrm{hp} \times 375}{3.5\ \mathrm{mph}} \\ &= 17{,}035.71 \ldots \text{ or } 17{,}000\ \mathrm{lb} \end{aligned}$$

The following parameters for the ASABE draft equation were obtained from Appendix V:

$$\begin{aligned} &F1 = 1.0\ (\text{fine textured, clay, soil}) \\ &C_1 = 62 \\ &C_2 = 5.4 \\ &C_3 = 0. \end{aligned}$$

Rearrange the ASABE equation for draft to solve for the machine width (w):

$$\begin{aligned} w(\mathrm{ft}) &= \frac{D_{\mathrm{F}}}{F_{\mathrm{i}} \times \left[C_1 + (C_2 \times V) + \left(C_3 \times V^2\right)\right] \times T_{\mathrm{d}}} \\ &= \frac{17{,}000}{1.0 \times \left(62 + (5.4 \times 3.5) + \left(0 \times 3.5^2\right)\right) \times 6} \\ &= \frac{17{,}000}{485.4} \\ &= 35.022 \ldots \text{ or } 35\ \mathrm{ft} \end{aligned}$$

The 185 PTO horsepower tractor will be able to pull an offset disk harrow up to 35 ft wide in a clay soil when operating at the low end of the typical speed and efficiency ranges.

The draft of a secondary tillage field cultivator is calculated as pounds of force per tool (shovel, sweep, etc.) plus a speed factor. Therefore, the number of shanks determines the size of the cultivator. For a cultivator, the drawbar horsepower equation is converted to:

$$W(\text{shanks}) = \frac{D_F}{F_i \times \left[C_1 + (C_2 \times V) + \left(C_3 \times V^2\right)\right] \times T_d}$$

The first step in determining the size of cultivator than can be pulled by the 159 hp tractor is determining the number of shanks for the cultivator. Assume the tillage depth T_d is 3 inches. From Appendix V, the machine parameters for a secondary tillage field cultivator are:

$$\begin{aligned} F_1 &= 1.0 \\ C_1 &= 19 \\ C_2 &= 1.8 \\ C_3 &= 0. \end{aligned}$$

Solving the ASABE draft equation for w (in this case number of tools or shovels):

$$\begin{aligned} w &= \frac{D_F}{F_i \times \left[C_1 + (C_2 \times V) + \left(C_3 \times V^2\right)\right] \times T_d} \\ &= \frac{17{,}000}{1.0 \times \left(19 + (1.8 \times 6) + \left(0 \times 6^2\right)\right) \times 3} \\ &= \frac{17{,}000}{89.4} \\ &= 190.156 \text{ or } 191 \text{ tools or shanks} \end{aligned}$$

The 185 PTO horsepower tractor will be able to pull a field cultivator with 191 shanks. The width of the cultivator depends on the number of rows of shanks and the spacing between each shank. Assume the cultivator will have three rows of shanks. The second and third row staggered equal distance between the front row shanks. The front row shanks are spaced 21 inches apart. This arrangement would have 191 shanks (64, 63, and 64). The width of the frame is 112 ft wide (64 shanks or tools multiplied by 21 inches and divided by 12 in/ft). The effective width includes one-half of the spacing on each end of the first and third row, 112 + 10.5 + 10.5 = 133 ft.

Appendix V presents the draft of equipment in the form found in the ASABE Standards. Other sources may provide draft figures for machines in pounds per foot. If these values are used, the drawbar horsepower equation does not need to be modified each time, but the calculations will not be as accurate as this example problem.

10.5 Costs of Machinery

The following sections discuss the elements that contribute to the cost of owning and operating agricultural machinery. An understanding of the types of costs and their impact on the profitability of the enterprise improves our ability to make meaningful decisions regarding the management of agricultural equipment.

The best information is the actual costs of the machine, but unfortunately the total cost of a machine is not known until the machine has reached the end of its serviceable life. Therefore, cost determinations must be based on estimations. To make these estimations realistic and reliable, they must be based on past machine performance and cost records. The following sections will discuss the typical costs of owning and operating machinery as well as methods that can be used to estimate the costs of agricultural equipment.

Generally, machinery costs are classified into two groups, ownership costs (fixed costs) and operating costs (variable costs). Fixed and variable costs are:

Fixed costs	Variable costs
1. Depreciation	6. Repair and maintenance
2. Interest on investment	7. Fuel
3. Taxes	8. Oil
4. Shelter	9. Labor
5. Insurance	10. Consumables

10.5.1 Fixed Costs

Fixed costs are independent of machine use and occur whether or not the machine is used. They are referred to as the cost of ownership. Each fixed cost is estimated on a calendar year or an annual basis. The common fixed costs are:

Depreciation
Interest on investment
Taxes
Shelter
Insurance

10.5.1.1 Depreciation

Depreciation is the loss in value of a machine with the passage of time, whether or not it is used. Depreciation can be regarded as the amount of money that should be saved each year as a machine is used so that, at the end of its useful life, this money along with the remaining value of the machine (salvage value) could be used to replace it. Several choices exist in the way by which depreciation can be figured for

cost and/or tax purposes. All depreciation methods require an estimation of the machine service life. The simplest method is straight line depreciation:

$$\frac{\$}{\text{yr}} = \frac{P - \text{SV}}{\text{yr}}$$

where \$/yr = annual depreciation; P = purchase price; SV = salvage value; yr = years of service.

Problem Determine the annual depreciation for a machine with a purchase price of \$15,400, a salvage value of \$800.00, and an expected life of 8 years.

Solution

$$\begin{aligned}\frac{\$}{\text{yr}} &= \frac{P - \text{SV}}{\text{yr}} \\ &= \frac{15{,}400.00 - 800.00}{8} \\ &= 1825.00\,\frac{\$}{\text{yr}}\end{aligned}$$

The annual straight line depreciation is \$1825.00 per year.

10.5.1.2 Interest on Investment

An interest cost should be used because the money tied up in purchasing a machine could have been used for another purpose or invested. When money is owed on a machine, the annual interest charges added to the depreciation can be used to estimate yearly costs of ownership. A method that includes the yearly costs of ownership and the time value of money is called capital recovery factor (CRF). CRF can be calculated by:

$$R = \left\{ (P - S) \times \left[\frac{\left(\frac{i}{q}\right) \times \left(1 + \frac{i}{q}\right)^{nq}}{\left\{\left(1 + \frac{i}{q}\right)^{nq}\right\} - 1} \right] \right\} + \frac{Si}{q}$$

where R = one of a series of equal payments due at the end of each compounding period; q = times per year; P = principal amount; i = interest rate as compounded q times per year; n = life of the investment in years; S = salvage value, \$.

Problem Determine the capital recovery factor for a machine that cost \$125,000.00 and has a salvage value of \$3000.00. A 10-year loan is used to purchase the machine with an interest rate of 10.5% per year.

Solution

$$R = \left\{ (P - \mathrm{S}) \times \left[\frac{\left(\frac{i}{q}\right) \times \left(1 + \frac{i}{q}\right)^{nq}}{\left\{\left(1 + \frac{i}{q}\right)^{nq}\right\}\text{-}1} \right] \right\} + \frac{Si}{q}$$

$$= \left\{ (\$125,000.00 - \$3000.00) \times \left[\frac{\left(\frac{0.105}{1}\right) \times \left(1 + \frac{0.105}{1}\right)^{10^{\mathrm{x}}1}}{\left\{\left(1 + \frac{0.105}{1}\right)^{10^{\mathrm{x}}1}\right\} - 1} \right] \right\}$$

$$+ \frac{\$3{,}000.00'0.105}{1}$$

$$= \left\{ \$122,000 \times \left(\frac{0.105 \times 2.714\ldots}{2.714\ldots - 1} \right) \right\} + \$\,315.00$$

$$= \{\$122,000'0.166\ldots\} + \$315.00$$

$$= \quad 20{,}598.3912 \text{ or } 20{,}600.00\ \frac{\$}{\mathrm{yr}}$$

The CRF for this machine is $20,600.00 per year.

10.5.1.3 Taxes

Any property and sales taxes paid on the equipment must be included as a fixed cost. Local rates should be used, but if they are not available, an estimate of the annual taxes for agricultural machinery is 1% of remaining value.

Problem What is the annual tax during the second year of ownership for a $55,000.00 machine when the expected life is 12 years? The salvage value is $500.00.

Solution The first step is to determine the value of the machine at the beginning of the second year. The value at the beginning of the second year is determined by the amount of depreciation that occurred during the first year. Assuming straight line method:

$$\frac{\$}{\mathrm{yr}} = \frac{\$\ 55{,}000.00 - \$500.00}{12} = 4541.666\ldots \text{ or } 4540.00\,\frac{\$}{\mathrm{yr}}$$

The value of the machine at the beginning of the second year is:

$$\$ = \$55{,}000.00 - \$4540.00 = \$50{,}460.00$$

The annual taxes are:

$$\frac{\$}{\mathrm{yr}} = \$50{,}460.00 \times \frac{0.01}{\mathrm{yr}} = 504.60\,\frac{\$}{\mathrm{yr}}$$

10.5.1.4 Shelter

A cost of shelter should be assigned to machinery. If a shelter is used, the cost of the shelter can be assigned over the life of the machine. If the machine is not sheltered, a cost should still be assigned because the resale value of a machine that has not been sheltered will be less than one that has been. An estimate for the annual cost of shelter is 0.75% of the value of the machine at the beginning of the year.

Problem What is the annual cost of shelter during the fourth year for a $4500.00 machine when the expected life is 5 years and the salvage value is $1500.00?

Solution The first step is to determine the value of the machine at the beginning of the fourth year. Assuming straight line depreciation, the annual depreciation is:

$$\frac{\$}{\text{yr}} = \frac{\$4500.00 - \$1500.00}{5} = 600.00 \frac{\$}{\text{yr}}$$

The value of the machine at the beginning of the fourth year is:

$$\begin{aligned} \$ &= \$4500.00 - \left(\frac{600.00\ \$}{\text{yr}} \times 3\ \text{yr} \right) \\ &= \$4500.00 - \$1800.00 = \$2700.00 \end{aligned}$$

The cost of the shelter during the fourth year is:

$$\frac{\$}{\text{yr}} = \$2{,}700.00 \times \frac{0.0075}{\text{yr}} = 20.25 \frac{\$}{\text{yr}}$$

A shelter cost of $20.25 should be used during the fourth year for this machine.

10.5.1.5 Insurance

Any liability or replacement insurance carried on the machine should be included. An estimate for the annual cost of insurance is 0.25% of the remaining value at the beginning of the year.

Problem Determine the lifetime insurance cost for a $125,500.00 machine when the expected life is 15 years and the salvage value is $10,000.00.

Solution The annual insurance cost for a machine is determined by multiplying the insurance factor times the value of the machine at the beginning of the year. Summing the annual insurance costs will produce the lifetime insurance cost for a machine. Because of depreciation, the value of the machine declines each year, and therefore the annual insurance cost declines each year. This problem can be solved by using a complex equation or using the same method as the previous examples, but it is also an example of a problem that can be solved using a spreadsheet (Table 10.1). Assuming straight line depreciation, the life time cost of insurance is $2685.00.

Table 10.1 Spreadsheet for determining lifetime insurance costs

Purchase price	$125,500.00	
Insurance factor	0.0025	
Annual depreciation	$7700.00	
Year	Value	Insurance cost
1	$125,500.00	$313.75
2	$117,800.00	$294.50
3	$110,100.00	$275.25
4	$102,400.00	$256.00
5	$94,700.00	$236.75
6	$87,000.00	$217.50
7	$79,300.00	$198.25
8	$71,600.00	$179.00
9	$63,900.00	$159.75
10	$56,200.00	$140.50
11	$48,500.00	$121.25
12	$40,800.00	$102.00
13	$33,100.00	$82.75
14	$25,400.00	$63.50
15	$17,700.00	$44.25
	Sum	$2685.00

The total cost of insurance over the lifetime of the machine is $2685.00

The annual cost of owning a piece of equipment is the sum of the fixed costs listed above. Notice that at this point, no mention has been made of machine use.

With accurate records, the annual cost of a machine can be determined by figuring the cost in dollars per year for each of the five fixed costs. Another approach is to combine the five items into an annual fixed cost percentage (FC%). Cost analysis of data indicates that the FC% times the purchase price of the machine is an acceptable estimate for the annual ownership costs of a machine:

$$\text{Annual ownership cost (AOC)} = \text{FC}\% \times \text{P}$$

An ownership cost percentage can be estimated by:

$$C_o = 100 \times \left(\left(\frac{1 - S_v}{L} \right) + \left(\frac{1 + S_v}{2} \times l \right) + K_2 \right)$$

where C_o = ownership cost percentage; S_v = salvage value factor (percent of salvage value compared to the purchase price) of machine at end of machine life (year L), decimal; L = machine life, yr; l = annual interest rate; K_2 = ownership cost for taxes, housing, and insurance, decimal.

Problem What is the ownership cost percentage for a machine that has an expected life of 10 years? The purchase price was $23,000. Assume a factor of 2% for taxes, housing, and insurance. The machine has a salvage value of $3,400.00.

Solution The ownership cost percentage is determined using the previous equation. This equation requires the salvage factor as a percent. To determine the percent, divide the salvage value by the purchase price and multiply by 100. The salvage factor is:

$$\text{Salavage factor } \% = \frac{\$3400.00}{\$23{,}000.00} \times 100 = 14.78\ldots \text{or } 15\%$$

The fixed cost percent is:

$$\begin{aligned} C_{\text{o}} &= 100 \times \left(\left(\frac{1 - S_{\text{v}}}{L} \right) + \left(\frac{1 + S_{\text{v}}}{2} \times l \right) + K_2 \right) \\ &= 100 \times \left(\left(\frac{1 - 0.15}{10} \right) + \left(\frac{1 + 0.15}{2} \times 0.10 \right) + 0.02 \right) \\ &= 100 \times (0.085 + 0.0575 + 0.02) \\ &= 100 \times 0.1625 = 16.25 \text{ or } 16\% \end{aligned}$$

Problem What is the annual ownership cost for a $150,000.00 combine when the fixed cost percentage is 18%?

Solution

$$\text{AOC}\left(\frac{\$}{\text{yr}} \right) = \text{FC}\% \times P = 0.18 \times \$150{,}000.00 = 27{,}000.00 \ \frac{\$}{\text{yr}}$$

10.5.2 Variable Costs

Variable costs are associated with the operation of a machine and occur only when the machine is used. The term operating costs frequently is used to describe variable costs. Variable costs are usually figured on an hourly basis, but they can be figured using acres, bales, or any other appropriate unit. The common variable costs are:

Repairs and maintenance
Fuel
Oil
Labor
Consumables

10.5.2.1 Repairs and Maintenance

The costs of repair and maintenance are related to the type of machine, the purchase price, and the hours of use. The repair and maintenance costs can be estimated using the following equation:

$$C_{\text{rm}} = \text{RF1} \times P \times \left(\frac{h}{1000}\right)^{\text{RF2}}$$

where C_{rm} = accumulated repair and maintenance cost ($); RF1 and RF2 = repair and maintenance factors (Appendix IV); P = machine price in current dollars, multiply original price by $(1 + i)^n$ where i is the average inflation rate and n is the age of the machine to adjust for inflation h = accumulated use of machine (h).

Problem Estimate the accumulated repair and maintenance costs for a self-propelled combine that was purchased 4 years ago for a price of $90,000.00. The machine has 1200 hr of use, and the average inflation has been 6.5%.

Solution The first step is to adjust the price of the machine for inflation:

$$\begin{aligned}\$ &= \$90{,}000.00 \times (1+i)^n \\ &= \$90{,}000.00 \times (1+0.065)^4 \\ &= \$90{,}000.00 \times 1.286\ldots \\ &= 115{,}781.9\ldots \text{ or } \$120{,}000\end{aligned}$$

Next the repair and maintenance costs can be estimated:

$$\begin{aligned}C_{\text{rm}} &= \text{RE1} \times P \times \left(\frac{h}{1000}\right)^{\text{RF2}} \\ &= 0.04 \times \$120{,}000.00 \times \left(\frac{1200}{1000}\right)^{2.1} \\ &= \$4800.00 \times 1.466\ldots \\ &= 7039.1 \quad \ldots \quad \text{or} \quad \$7000.00\end{aligned}$$

10.5.2.2 Fuel

The fuel consumption for an engine is influenced by the size of the engine and the percent of load. Average annual consumption can be estimated using the procedures printed in ASABE Standard D497.4 FEB03:

$$Q_{\text{avg}} = 0.0305 \times P_{\text{pto}}$$

where Q_{avg} = average gasoline consumption, L/hr; P_{pto} = maximum PTO power, kW.

$$Q_{\text{avg}} = 0.06 \times P_{\text{pto}}$$

where Q_{avg} = average gasoline consumption, gal/hr; P_{pto} = maximum PTO power, hp.

These equations must be multiplied by 0.73 for diesel and by 1.20 for liquefied petroleum gas (LPG) tractors.

Problems Estimate the annual fuel consumption for a 125 PTO Hp diesel tractor that will be used for 850 hr per year.

Solution The first step is to use the equation to determine the hourly use.

$$\frac{\text{gal}}{\text{hr}} = 0.06 \times 125 \times 0.73 = 5.475 \text{ or } 5.5 \frac{\text{gal}}{\text{hr}}$$

The second step is the multiply the hourly use by the hours per year:

$$\frac{\text{gal}}{\text{yr}} = 5.5 \frac{\text{gal}}{\text{hr}} \times 850 \frac{\text{hr}}{\text{yr}} = 4675 \text{ or } 4700 \frac{\text{gal}}{\text{yr}}$$

Estimating the fuel consumption for a specific operation requires determining the total tractor power for that operation. ASABE Standard D497.4 provides a method for estimating fuel consumption for a specific operation.

10.5.2.3 Oil

The oil cost in dollars per hour will be the product of the oil consumption (gal/hr or L/hr) during operation and oil changes and the oil price ($/qt or $/L). The total oil used (gal/hr) on a per hour basis can be estimated assuming manufacturer's recommended change interval by:

Gasoline	$(0.00011 \times P) + 0.00657$
Diesel	$(0.00021 \times P) + 0.00573$
LPG	$(0.00008 \times P) + 0.00755$

where P = rated power, hp.

The total oil used (L/hr) on a per hour bases can be estimated by:

Gasoline	$(0.000566 \times P) + 0.02487$
Diesel	$(0.00059 \times P) + 0.02169$
LPG	$(0.00041 \times P) + 0.02$

where P = rated power, hp.

Problem Determine the amount of oil that will be used by a 120 PTO horsepower diesel tractor.

Solution

$$\frac{\text{gal}}{\text{hr}} = (0.00021 \times 120) + 0.00573 = 0.03093 \text{ or } 0.031 \frac{\text{gal}}{\text{hr}}$$

10.5.2.4 Labor

The hourly wage for labor to operate the equipment in dollars per hour. When the owner is the operator, a labor cost must be included to determine the true costs.

10.5.2.5 Consumables

Some machines, such as balers, have twine, netting, or other materials that are consumed as a part of the machine operation.

Thus, the total hourly operating cost (THOC), in dollars per hour, of a machine is the sum of the repairs and maintenance cost, the fuel cost, the oil cost, the labor cost and the consumable cost.

10.5.3 Annual Cost

The annual cost for a machine is the sum of the fixed and variable costs.

Problem Determine the annual costs for a $35,000.00 grain drill that is used 120 hr per year. It has an expected life of 10 years and a salvage value of $1000.00. It is pulled by a 98 horsepower diesel tractor. Assume an interest rate of 8%.

Solution The annual cost is the sum of the fixed costs and the variable costs. The fixed costs can be determined by calculating each individual cost or by using the ownership cost equation to determine the ownership cost percentage. For this example, the ownership cost equation will be used.

Fixed Costs The ownership cost equation requires salvage value expressed as a percentage.

Salvage value factor:

$$\text{Salvage factor } \% = \frac{\$1000}{\$35{,}000} \times 100 = 2.857 \ \ldots \text{ or } 2.8\%$$

Total fixed cost percent:

$$\begin{aligned} C_{\text{o}} &= 100 \times \left(\left(\frac{1 - S_{\text{v}}}{L} \right) + \left(\frac{1 + S_{\text{v}}}{2} \times l \right) + K_2 \right) \\ &= 100 \times \left(\left(\frac{1 - 0.028}{10} \right) + \left(\frac{1 + 0.028}{2} \times 0.08 \right) + 0.02 \right) \\ &= 100 \times (0.0972 + 0.04112 + 0.02) \\ &= 100 \times 0.15832 = 15.832 \text{ or } 16\% \end{aligned}$$

Total fixed costs:

$$\frac{\$}{\text{yr}} = \$35{,}000.00 \times \frac{0.16}{\text{yr}} = 5600.00 \frac{\$}{\text{yr}}$$

Variable costs: annual variable costs = repair and maintenance + fuel + oil + labor

Repair and maintenance:

$$\begin{aligned} C_{\text{rm}} &= \text{RF1} \times P \times \left(\frac{h}{1000}\right)^{\text{RF2}} \\ &= 0.32 \times \$35{,}000.00 \times \left(\frac{120}{1000}\right)^{2.1} \\ &= 0.32 \times \$35{,}000.00 \times 0.0116\ldots \\ &= 130.466\ldots \text{ or } 130.00\ \frac{\$}{\text{yr}} \end{aligned}$$

Fuel: The fuel cost for the grain drill is determined by the power and fuel efficiency of the tractor. Estimating tractor fuel costs for specific operation is not included in this text. See ASABE D496 for this information. Average fuel consumption based on the fuel type and power of the tractor can be estimated using the information from ASABE EP496.3 FEB06.

The fuel use (gal/hr) is:

$$\begin{aligned} Q_{\text{avg}} &= 0.06' P_{\text{pto}} \times 0.73 \\ &= 0.06 \times 98 \times 0.73 \\ &= 4.2924 \text{ or } 4.3\ \frac{\text{gal}}{\text{hr}} \end{aligned}$$

The fuel cost is (assuming fuel is 2.25 $/gal):

$$\begin{aligned} \frac{\$}{\text{yr}} &= \frac{4.3\ \text{gal}}{\text{hr}} \times \frac{2.25\ \$}{\text{gal}} \times \frac{120\ \text{hr}}{\text{yr}} \\ &= 1161 \text{ or } 1200.00\ \frac{\$}{\text{yr}} \end{aligned}$$

Oil costs:

$$\begin{aligned} \frac{\text{gal}}{\text{hr}} &= (0.00021 \times P) + 0.00573 \\ &= (0.00021 \times 98) + 0.00573 \\ &= 0.02631\ \frac{\text{gal}}{\text{hr}} \end{aligned}$$

Assuming an oil cost of 4.00 $/qt:

$$\begin{aligned} \frac{\$}{\text{yr}} &= \frac{4.00\$}{qt} \times \frac{4\,qt}{\text{gal}} \times \frac{0.02631\,\text{gal}}{\text{hr}} \times \frac{120\,\text{hr}}{\text{yr}} \\ &= 50.51\ldots \text{or } 50.50\ \frac{\$}{\text{yr}} \end{aligned}$$

Labor: Labor costs are determined by multiplying the annual use by the tractor operator cost in $/hr.

$$\frac{\$}{\text{yr}} = \frac{120\,\text{hr}}{\text{yr}} \times \frac{\$10.00}{\text{hr}} = 1200.00\ \frac{\$}{\text{yr}}$$

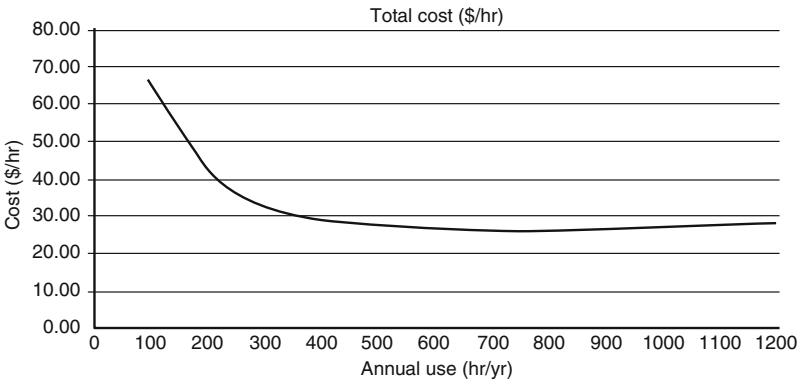

Fig. 10.1 Total costs per hour of use

The total cost of owning and using the grain drill 120 hr per year is:

$$\text{Total annual cost} = \text{Annual fixed costs} + \text{Annual variable costs}$$

$$\begin{aligned}\text{Total annual cost} &= \text{Annual fixed costs} + \text{Annual variable costs}\\ &= 5600.00\frac{\$}{\text{yr}} + \left(130.00\frac{\$}{\text{yr}} + 1200.00\frac{\$}{\text{yr}} + 50.50\frac{\$}{\text{yr}} + 1200.00\frac{\$}{\text{yr}}\right)\\ &= 5600.00\frac{\$}{\text{yr}} + 2580.50\frac{\$}{\text{yr}}\\ &= 8150.50 \text{ or } 8200\frac{\$}{\text{yr}}\end{aligned}$$

Machinery costs in dollars per year are useful for the owner/operator of a machine, but for custom work, the operator needs to know the costs in terms of dollars/acre, dollars/hour, dollars/bale, etc. The cost of a machine on a unit volume basis is influenced by the annual use because as the annual use increases, the fixed costs are spread out over more units. This makes the fixed costs less per unit. To illustrate this point, Fig. 10.1 shows the costs per acre for the grain drill in the previous problem for an annual use ranging from 100 to 1200 hr per year.

Note that the dollars per hour costs decrease until about 700 hr, and then they start backup. This is because the equation used by ASABE to estimate repair and maintenance costs is designed to increase repair costs as the machine uses increases.

10.6 Ways to Reduce Costs

A feature of agriculture is that the buyer usually sets the price the producer receives for their products; therefore, the best way to increase profits is to reduce production costs. No single factor will keep ownership and operating costs of tractors and machinery to a minimum, but good management of the following factors will reduce the production costs of machinery.

10.6.1 Width Utilization

The effective width is always less than the width of the machine, except for row crops, because most operators overlap each round slightly to prevent skips. Any excessive overlap reduces the effective capacity of the machine and increases the cost per acre.

10.6.2 Time Utilization

Any time that a machine is not performing its designed task, when it could be, equals lost productivity. Several practices can be used to reduce lost time. First, adjusting and lubricating of the machine should be kept to a minimum. Even better, you should do as much of the maintenance as possible when conditions prevent the machine from being in the field.

Second, breakdowns can be minimized by avoiding overloads and by a complete preventive maintenance program. Any machine is more likely to break down or to need additional maintenance if it is overloaded or misused.

Third, a proper field layout will keep turning at the end of the row or round to a minimum. There is an optimum pattern for every field shape and size of machine. Machinery management texts provide more information on this topic.

Another idea is to reduce the time required to refill seed, fertilizer, and chemicals by using the largest practical size of hopper or tank. In addition, the equipment used to load the tank or the hopper should have the capacity to fill it in a reasonable time.

10.6.3 Matching Tractors and Machines

Tractors furnish power most economically when operated at or near the rated load. If the load is too small, it may be increased by widening the machine or by using two machines in tandem. Increasing the speed also increases the effective tractor load. If all of the tractor power is not being utilized and it is not feasible to increase the speed, fuel costs can be reduced by shifting up into a higher gear and reducing the throttle. (Check the owner's manual before attempting this.)

10.6.4 Reducing Original Investment

The initial cost of a machine is a major factor in determining the fixed cost of owning and operating farm machinery. The initial cost can be reduced by buying used equipment or by building equipment and machinery in the farm shop. Both of these strategies substitute human labor for some of the initial cost.

10.6.5 Increasing Annual Use

As we discovered in the section on calculating costs, the more a machine is used, the less the cost per unit will be. Usage can be increased by joint ownership, by increasing the size of the enterprise, by doing custom work, or by increasing the working season by diversifying production.

10.6.6 Increasing Service Life

Ensuring that the machine lasts as long as possible is one way of reducing the need for the initial cost of a new machine. The service life can be extended through proper maintenance, careful adjustments, avoidance of overloads, and using skilled operators. The useful life also is extended through proper storage during the off-season.

10.7 Break-Even Use

In the previous section, we introduced the notion that the total cost per acre or hour decreases as annual use increases. This is the basis of BEU. For some operations, it may be more profitable to consider hiring contract workers instead of owning and operating one's own machine. The decision to hire may hinge on the break-even usage, that is, the amount of use for which the costs of owning a machine are the same as the costs of hiring a custom operator.

Suppose for a given machine that the product of FC% and *P* equals $1000. Also, suppose that the operating costs are $ 4.00 per acre. The total annual cost (TAC) equation would be:

$$\text{TAC} = \$1000.00 + (\$4.00 \times \text{A})$$

where A = acres of use.

Next calculate the values of TAC for acre (*A*) values of 10, 50, 100, 200, and 500 acres. The result is shown in Table 10.2.

Then if we wish to determine the cost of using the machine on a per-acre basis, we divide the TAC by the acres for each situation and get the values shown in Table 10.3.

Table 10.2 Break-even use

Acres	Total annual cost (TAC)
10	$1040
50	1200
100	1400
200	1800
500	3000

Table 10.3 Cost per acre

Acres	TAC	Cost per acre
10	$1040	$104.00
50	1200	24.00
100	1400	14.00
200	1800	9.00
500	3000	6.00

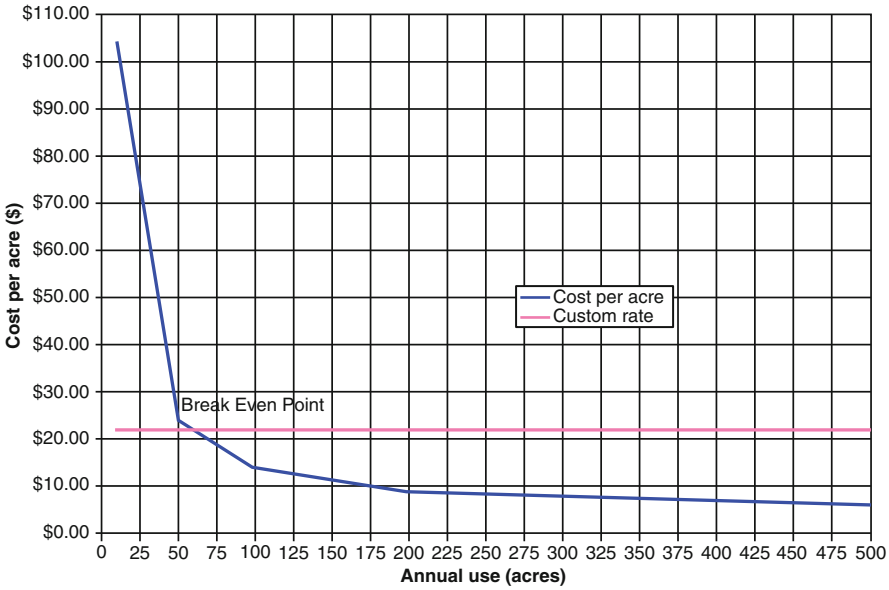

Fig. 10.2 Break-even analysis for $22.00 per acre custom rate

A comparison of the various levels of use shows that the cost per acre decreases as use increases. The break-even analysis in Fig. 10.2 shows that for a custom rate of $21.00 per acre, the cost for an annual use of about 60 acres per year it is more economical to hire work. At annual use of over 60 acres per year, it is more economical to own the machine and do the work yourself.

This same method can be used to determine the break-even point for costs with units different than dollars per acre. For the process to result in good information, the custom rate and the total costs must be in the same units.

The BEU can be determined by the following equation:

$$\text{BEU} = \frac{\text{AOC}}{\text{CR} - \text{OPC}}$$

where BEU = break-even use, unit of use; AOC = annual ownership costs, $/yr; CR = custom rate, $/unit of use; OPC = operating costs, $/unit of use.

Although this analysis indicates a hard-and-fast decision for a particular amount of use, the ownership—custom hiring decision—is tempered by other factors. Table 10.4 lists some advantages and disadvantages of custom hiring of farm equipment. It is most important to use consistent units with each of the terms. If the custom rate is in dollars per acre, the operating cost must be in dollars per acre. In this case, the units of the answer will be in acres per year.

Table 10.4 Advantages and disadvantages of custom hiring farm equipment

Advantages	Disadvantages
1. No ownership costs	1. May not be possible to schedule when needed
2. Cost of equipment can be invested in other enterprises	2. Less control of quality of work
3. Hired equipment usually supplies labor	3. Increased potential for losses because of delays
4. Less equipment is needed by owner, particularly specialized	4. Increased risk of spreading weed seeds and diseases
5. Owner can take advantage of newest machinery and techniques	5. Costs for large jobs may be higher than owning machines
6. Producer with small jobs can gain benefits of large machines	6. Small jobs have a greater chance of being postponed
7. Custom operator is responsible for repairs, maintenance, and materials	7. Producer may not be able to utilize own labor freed up by custom hiring

Problem What is the BEU in acres for a $20,000 machine if the FC% is 22%, the operating costs are $9.00 per hour, and the custom rate is $9.60 per acre?

Solution

$$\text{BEU (ac)} = \frac{\text{AOC}}{\text{CR} - \text{OPC}} = \frac{\$20{,}000 \times 0.22}{9.60\frac{\$}{\text{ac}} - 9.00\frac{\$}{\text{hr}}}$$

The calculation is not completed because the units are not correct. The custom rate and the operating costs must have the same units to be subtracted. When the desired break-even point is in acres, both the custom rate and the operating costs must have the units of dollars per acre. The dollars per hour units must be converted to dollars per acre:

$$\frac{\$}{\text{ac}} = \frac{\$}{\text{hr}} \times \frac{\text{hr}}{\text{ac}}$$

Hours per acre is more commonly expressed as acres per hour, the capacity of a machine. Assume the effective capacity of the machine is 2.50 acres per hour:

$$\begin{aligned}\text{BEU (ac)} &= \frac{\text{AOC}}{\text{CR} - \text{OPC}} = \frac{\$20{,}000 \times 0.22}{9.60\frac{\$}{\text{ac}} - 9.00\frac{\$}{\text{hr}}} \\ &= \frac{\$20{,}000 \times 0.22}{9.60\frac{\$}{\text{ac}} - \left(9.00\frac{\$}{\text{hr}} \times \frac{1\ \text{hr}}{2.50\ \text{ac}}\right)} = 733.33\ldots \text{ or } 730\ \text{ac}\end{aligned}$$

10.8 Maintenance Schedules

Maintenance is the care given to a machine to ensure that it operates correctly and that it receives the required lubrication and adjustments. All machines require maintenance. Failure to provide adequate maintenance can shorten the life of the machine and/or increase its operating costs. Manufacturers specify the amount of resources that a machine will need to maintain its operation. The owner's/operator's responsibility is to ensure that the maintenance is accomplished on schedule, based on the manufacturer's recommendations in the owner's manual. This schedule must be followed for the machine to reach its designed potential in performance and longevity.

10.9 Metric Problems

The process used for estimating costs is the same for both the SI and US customary systems. When estimating the costs for the metric system, substitute the appropriate costs. Appendix V provides the parameters needed to calculate draft using the ASABE equation. An example follows for the SI system.

Problem A chisel plow equipped with 5 cm-wide shovels is used for primary tillage in a wheat field. Depth of tillage is 15 cm. The chisel plow width is 13.7 m. The chisel shank spacing is 0.3 m. Plowing speed is 10 km/hr. The soil is a silt loam (medium texture). What is the drawbar power required to pull the chisel plow?

From Appendix V:

$$\begin{aligned} F_2 &= 0.7 \\ C1 &= 91 \\ C2 &= 5.4 \\ C3 &= 0. \end{aligned}$$

Compute the number of tools (shanks):

$$w_{\text{Tool}} = \frac{w_{\text{match}}}{w_{\text{tool spacing}}} = \frac{13.7 \text{ m}}{0.3 \text{ m}} = 45.666 \text{ or } 45 \text{ tools}$$

Calculate the draft in newtons:

$$\begin{aligned} D_{\text{F}} &= F_{\text{i}} \times \left[C_1 + (C_2 \times V) + \left(C_3 \times V^2\right)\right] \times w \times T_{\text{d}} \\ &= 0.7 \times \left[91 + (5.4 \times 10) + \left(0 \times 10^2\right)\right] \times 45 \times 15 \\ &= 68{,}512.5 \text{ or } 68{,}000 \text{ N} \end{aligned}$$

Calculate the drawbar power. Recall that draft is a force:

$$\begin{aligned} P_{\text{DbkW}} &= \frac{F \times V}{60{,}000} \\ &= \frac{68{,}000 \text{ N} \times 10 \frac{\text{km}}{\text{h}}}{60{,}000} \\ &= 113.333 \text{ or } 113 \text{ kW} \end{aligned}$$

The cultivator will require a tractor with at least 113 kW.

Chapter 11
Sound and Noise

11.1 Objectives

1. Be able to understand the nature of sound and the basis of sound measurement, the decibel (dB)
2. Be able to compare different environmental sounds
3. Be able to understand how humans are affected by noise
4. Be able to become familiar with noise exposure standards and protection from excessive noise

11.2 Introduction

Humans live in a world of sound. Many sounds are quite pleasant, and persons who are not hearing impaired enjoy hearing voices, music, and many sounds of nature. People often listen for sounds that could warn of danger or the malfunctioning of equipment. Individuals have differing abilities to detect sound of varying intensities and frequencies. People also differ as well in their personal tolerance of and appreciation of sound.

Sound that is harsh and unpleasant (or unhealthy) is commonly referred to as noise. In recent years, the subject of noise has been given considerable attention, especially as it affects human health and behavior. The federal government through OSHA (Occupational Safety and Health Administration) has established noise exposure limits to prevent worker hearing loss and/or psychological stress due to excessive exposure to noise. OSHA does not have enough inspectors to ensure all work environments meet standards. It is up to individuals to understand the nature of sound and noise so they know when unhealthy environments may exist due to undesirable or unwanted sound.

11.3 What Is Sound

The sound that people hear is due to vibrations in air or substances that are transmitted to the hearing organs. What are perceived as sounds are sonic pressure waves that travel through the air or substances. When they interact with the eardrum

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and the other audio parts after entering the ear canal or by passing through the body, they are heard as sound. Thus, the eardrum responds to "sound pressure." Sound pressure can increase as much as 10,000 times as the intensity varies from the "threshold of hearing," the intensity of sound just barely detected by an average human ear, to the sound pressure created by a large jet engine operating nearby. People can "feel" loud sounds, and when they touch a vibrating body, the vibrations can pass through the body to the eardrum.

Another characteristic of sound is the frequency of the sonic pressure waves. Sound frequency is measured in cycles per second or Hertz (Hz). The range of frequencies that can be heard by humans varies from about 20 to 20,000 Hz, depending on the individual. The frequency heard by animals is different for each species and in some cases is outside the range of humans.

The frequency of the sound and the intensity of the sound must be considered together because for any frequency as the intensity of a sound increases at some point, the threshold of pain is reached. The threshold of pain for sound varies among individuals and for each species.

Human hearing also can distinguish between sounds that differ in quality, those combinations of frequencies and intensities that produce squealing, grating, grinding, or rasping sounds. When the frequencies and intensities are combined in suitable proportions, pleasant musical or vocal sounds result. Thus, the sounds that are heard can be quite complex, but their effects on humans are well established.

In this chapter, the concern is with that part of sound called noise and how it affects workers and their work. Generally, excessive noise can lead to hearing impairment, fatigue, annoyance, and interference with performance. Noise also can serve as a warning of equipment malfunction or a signal of needed maintenance. We frequently rely on sounds (or no sound) to tell us that equipment is performing satisfactorily.

11.4 How Sound Is Measured

The intensity of sound is measured in units of decibels (dB). The unit decibel is a ratio of any two of the three components of sound, power, pressure, and intensity. The human ear has the capability of distinguishing a wide range of sound intensity and frequencies. The range of sound pressure that an individual might be able to distinguish from the threshold of hearing to causing damage to the ears is over a million. Because the decibel scale is a ratio, to measure a single source of sound, a base line called a filter is used. Three standard filters are used. They are identified as A, B, and C. Filter A is less sensitive to very high and very low frequencies. The C filter is commonly used for high frequencies. The B filter falls in between the A and C. It is seldom used. When using a sound meter, it is important to select the desired filter and identify which filter was used when the measurement is recorded. This is accomplished by adding the units of dBA or dBC after the measurement.

To simplify the measurement of sound, decibel readings are based on an exponential scale of sound pressure levels. Remember that the decibel is not an absolute measure of the sound pressure but rather is a ratio of a measured sound pressure to a reference sound pressure. Also, because this sound scale is

exponential, a sound of 10 dB has an intensity 10 times greater than a sound of 0 dB, and a sound of 20 dB is 100 times more intense than 0 dB. Thus, a 10 dB difference in sound pressure level changes the intensity by 10 times, a 20 dB difference changes the intensity by 100 times, a 30 dB difference changes the intensity by 1000 times, and so on.

The basic instrument used to measure continuous sound is the sound-level meter. It consists of a microphone to pick up the sound, an amplifier, one or more frequency weighting networks, and a meter to display the sound level. Sound-level meters usually are self-contained and are small enough to be handheld although mounting them on a tripod is preferred.

Proper sound-level meter use involves careful placement of the microphone to avoid sound reflections that influence the readings. In measuring the noise exposure of an individual, the microphone is placed as close as possible to the subject's ear or where the ear would be in the work environment. Prior to use, the instrument must be calibrated against a known stable sound source.

11.5 Comparing Different Sounds

Table 11.1 shows some common sounds and the approximate sound pressure level associated with them.

Table 11.1 Decibel rating of common sounds

Sound pressure level (dB)		Sound description
188		Apollo lift-off, close
150		Jet engine, 10 ft away
140	Pain threshold	
130		Warning siren
125		Chain saw
120	Discomfort threshold	Loud thunder
115	Max under federal law	
110		Very loud music
105		Loud motorcycle or lawn mower
100	Very loud	Pneumatic air hammer
90		Cockpit of light plane, heavy truck
85		Average street traffic
80		Lathe, milling machine, loud singing
75		Vacuum cleaner, dishwasher
70		Average radio, noisy restaurant
65	Annoying	
60		Normal conversation, air conditioner
50		Light traffic, average office
40		Library, quiet office
30		Quiet room in home, audible whisper
20		Electric clock, faint whisper
10	Barely detectable	Rustle of leaves
0	Hearing threshold	

This chart may help you identify and classify sounds that you normally encounter; and if they are disturbing or otherwise unhealthy, you can avoid them or properly protect yourself from their adverse effects. Note that the values shown in the table are average values. Also, notice that almost identical sounds may come from different machines and situations. Further, individuals may differ in their tolerance of and classification of different sounds and noises. In specific situations and when determining if noise levels are acceptable under current standards, the equations in Sect. 11.7 must be used.

11.6 The Effect of Noise

As suggested previously, noise can have both psychological and physiological effects on people. Psychologically adverse noise mainly affects a worker's performance and state of well-being. Direct exposure to excessive noise may cause fatigue, distraction, annoyance, interference with communication, reduction in the memory function, and disturbance of rest and relaxation. Some or all of these effects may be involved in decreased performance in the workplace.

The main physiological effect of adverse noise is noise-induced hearing loss, which is irreversible damage to one or more parts of the hearing organs. Damage to hearing by loud noise may not become evident until years after the incident. However, high sound levels also can induce responses in other parts of the body, such as reduced blood circulation, change on the skin's resistance to electric current and a corresponding activation of the nervous system, increased muscle tension, changes in breathing patterns, and disturbance of sleep. These non-hearing-related noise responses are considered reversible and soon disappear when the noise source is removed.

Not all adverse noise is encountered in the workplace. We are surrounded by indoor and outdoor equipment that produce noise. Indoors such things as blenders and clothes washers can produce loud noises. Outside machines such as gas-powered tools, motorcycles, and boat engines can produce loud noises. In addition, we can be exposed to firearms, explosive devices, high-power speaker systems, snowmobiles, and many other sources of loud noises. Many of these items generate unusually intense sounds, but when we are preoccupied with the utility and the joy of using them, we are seldom aware of the noise they create or their potential for damaging our hearing.

11.7 Determining Noise Exposure

We must become more aware of our sound environment, determine acceptable exposure limits, and take any steps necessary to avoid overexposure and the potentially adverse psychological and physiological effects. OSHA standards require businesses compute the employee noise exposure. Noise exposure can be measured with an audiodosimeter or with a decibel meter. The following section will explain the recommended method using a decibel meter. This is accomplished using two rules.

1. When the sound level, L,[1] is constant over the entire work shift, the noise dose, D, in percent, is given by:

$$D = 100 \times \frac{C}{T}$$

where D = dose level (%); C = the total length of the work day (hr); T = the reference duration level corresponding to the measured sound level (L). (L can be determined by table or by equation)

2. When the work shift noise exposure is composed of two or more periods of noise at different levels, the total noise dose over the workday is given by:

$$D = 100 \times \frac{C_1}{T_1} + \frac{C_2}{T_2} + \ldots + \frac{C_n}{T_n}$$

where D = noise dose, %; $C(n)$ = the total time of exposure at a specific noise level; $T(n)$ = the reference duration for that level as given by Table 11.2 or equation.

The first equation determines the dose (%) for the employee. A dose of 100% is the maximum allowed.

The reference duration level (T) is computed using the following equation:

$$T = \frac{8}{2^{\left(L-90/5\right)}}$$

where T = reference duration; L = dBA exposure.

Problem Determine the sound dose for an individual who was subject to a sound of 55 dBA for 1.25 hr and a level of 105 dBA for 5.0 min.

Solution The dose equation requires a different reference duration (T) for each sound level and duration. The first step is to determine the value of T for each sound level and duration.

$$T_1 = \frac{8}{2^{\left(L-90/5\right)}} = \frac{8}{2^{\left(55-90/5\right)}} = \frac{8}{2^{-7}} = \frac{8}{0.0078125} = 1024 \text{ or } 1000$$

and

$$T_2 = \frac{8}{2^{\left(L-90/5\right)}} = \frac{8}{2^{\left(105-90/5\right)}} = \frac{8}{2^3} = \frac{8}{8} = 1$$

The next step is to determine the value for each exposure using the dose equation:

$$D = 100 \left(\frac{C_1}{T_1} + \frac{C_2}{T_2}\right) = 100 \times \left(\frac{1.25}{1000} + \frac{5.0 \text{ min} \times \frac{1 \text{ hr}}{60 \text{ min}}}{1}\right)$$

$$= 100 \times (0.00125 + 0.0833\ldots) = 8.458\ldots \text{ or } 8.4\%$$

The worker dose was 8%, well within the range of the maximum allowed of 100%.

[1] *CFR 1910.95(b)(2)

11.8 Exposure Guidelines

OSHA has provisions for employers to make accurate sound measurements in their places of business. The purpose is to ensure the workplace is safe for workers. OSHA limits sound exposure to 90 dB during an 8 hr work period. For sound levels above 90 dB(A), reductions in exposure time are required. Exposure is limited to 15 min of exposure per day to a sound level of 115 dB. A further aspect of the Act is that no impulsive or impact noise should exceed 140 dB. Also, noise abatement in excessively noisy work areas is required. If a workplace is deemed excessively noisy, workers must be provided with safety equipment and be required to use it.

Besides the OSHA regulations and the regulations set forth under the Federal Noise Control Act (administered by EPA), several other federal agencies oversee noise control in related industries such as aviation, residential and commercial construction, all aspects of ground transportation, and mining. References to these regulations can be found in different volumes of the CFR (Code of Federal Regulations) that involve noise control.

11.9 Controlling Noise

If objectionable, excessive or unhealthy noise situations are identified in any environment a course of action must be taken to eliminate or reduce the noise. This can be accomplished through design changes or the use of sound-absorbing materials. If that is not possible, workers must be provided human protective equipment such as earplugs, earmuffs, or specially designed helmets. Further, using Table 11.2 as a guide, potential exposure to excessive noise can be identified and avoided.

Table 11.2 Workplace maximum permissible noise exposure level versus daily exposure time[a]

Duration (hr/day)	Sound level (dBA)
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110
0.25	115
0.125	120
0.063	125
0.031	130

[a]CFR 1910.95(b)(2)

11.10 Metric Problems

This information is from OSHA, a US agency, and a metric equivalent is not available. However, since measurements are in the form of ratios, the measurements are the same in SI units and countries adopting metric units will likely have similar standards.

Chapter 12
Measuring Distance

12.1 Objectives

1. Be able to understand the advantages and disadvantages of the six common methods of measuring distance
2. Be able to use the six common methods of measuring distance
3. Be able to calibrate distance-measuring instruments
4. Be able to calculate a correction factor for a systematic error

12.2 Introduction

Measuring distance and angles with simple instruments are two common surveying procedures used in agriculture. Even though the instruments may be simple, a sufficient level of accuracy for many measuring jobs can be achieved with practice and careful work. In this chapter, you will become acquainted with the basic methods and techniques of measuring distances. The layout and measurement of angles are covered in Chap. 13.

12.3 Measuring Distances

Several simple methods and devices can be used for measuring distance. The principal ones are:

1. Pacing
2. Odometer
3. Taping or "chaining"
4. Stadia
5. Optical range finder
6. Electronic distance measuring (EDM)

One of the decisions that must be made when preparing to measure a distance is selecting the method or device to use because each device or method has advantages and disadvantages. In addition, the costs are different. The following sections will discuss each of these devices to help make that decision.

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First, it will be helpful to review the common units of distance and their conversion factors. The common U.S. Customary units are as follows:

1 foot (ft) = 12 inches (in)
1 yard (yd) = 3 feet (ft)
1 rod = 16.5 feet (ft) = 5.5 yards (yd)
1 mile (mi) = 5280 feet (ft) = 1760 yards (yd) = 320 rods

In the SI system, the units are:

1 meter (m) = 1000 millimeters (mm)
1 kilometer (km) = 1000 meters (m)

When using these common English units, the unit cancellation method is very useful for converting from one unit of measure to another.

12.3.1 Pacing

Pacing is the simplest and easiest method for measuring distance. Pacing is essentially counting the number of steps or paces, required to traverse a distance. Pacing is not just walking a distance; it is traversing a distance using a pace that is different from the normal walking step. A length of pace should be selected that is not too short or too long to be uncomfortable. This length is called the pace factor. A different length of pace should be used because many factors cause variations in the length of a person's step. Three of these are the roughness of the surface, the slope of the ground, and the type of vegetation.

Before pacing a distance, the intended use of the information must be considered. If the purpose of the pacing is to determine the number of rolls of barbed wire that are needed to complete a fence line, precision is not critical. Small variations in pace length and rounding to the nearest pace will produce acceptable results. For situations were more precision is critical, care must be taken to ensure that a consistent length pace is used, and partial paces should be recorded.

To measure a distance the individual paces the route and records the number of paces. The distance is calculated by multiplying the number of paces by the person's pace factor. A person's pace factor is determined by pacing a known distance of 200 to 500 feet several times and calculating the average length of pace using the number of paces and the length of the paced distance.

Problem An individual paces a 200.0 ft. distance three times and counts 62, 60, and 64 paces. What is the person's pace factor (PF)?

Solution To determine a pace factor, divide the measured distance by the average number of paces. The average number of steps ($\bar{x}$) is:

$$\bar{x} = \frac{62 + 60 + 64}{3} = 62$$

and the pace factor is:

$$\text{PF} = \frac{200 \text{ ft}}{62 \text{ paces}} = 3.225\ldots \text{ or } 3.2 \frac{\text{ft}}{\text{pace}}$$

Fig. 12.1 Odometer wheel

Once the pace factor is known, the length of an unknown distance can be determined by counting the number of paces required to cover the distance and multiplying the number of paces by the pace factor.

Problem An individual with a pace factor of 3.2 ft/pace counts 375 paces for an unknown distance. What is the distance in feet?

Solution The distance, in feet, equals the number of paces times the pace factor:

$$\text{ft} = 3.2\,\frac{\text{ft}}{\text{pace}} \times 375\ \text{paces} = 1200\ \text{ft}$$

One advantage of pacing is that it doesn't require any specialized equipment. The biggest disadvantage is that it requires being able to walk the route. It is not very useful for measuring distance in rough terrain, across swamps, or in any other terrains where an individual could not walk the distance or walk in a straight line.

With practice it is possible to pace a distance with an error of less than 2 feet per 100 feet.

12.3.2 Odometer

An odometer is a mechanical device that is used to record revolutions. An odometer wheel is a wheel with an odometer attached to the wheel with a mechanism that translates revolutions to distance (Fig. 12.1).

The common odometer wheel counts the revolutions of a wheel and shows the distance traveled on a multiple dial readout (Fig. 12.2). The drive train can be designed to produce readings in whole feet, decimal feet, feet, and inches or meters. The principle of an odometer wheel is the circumference of a wheel times the

Fig. 12.2 Odometer wheel reading of 1850 ft

number of revolutions equals distance; therefore, any wheel can be used as long as the diameter of the wheel is known and the number of revolutions is counted.

Experience has shown that the accuracy of odometer wheels is influenced by the surface and the topography. An odometer wheel designed to be used on hard surfaces will not be as accurate when used in grass or tall weeds. In these situations, the accuracy is improved if the wheel is recalibrated for the surface on which it will be used. See Sect. 12.4.1 for an example of the calibration procedure.

When an odometer wheel is used, the readout should be reset to zero before starting; then the distance traveled can be read directly. If another type of wheel is being used, the distance traveled is equal to pi (π) times the diameter multiplied by the number of revolutions:

$$D\,(\text{ft}) = \pi \times \text{Dia} \times N$$

where D = measured distance; $\pi = 3.14$; Dia = wheel diameter (ft); N = number of wheel revolutions.

Problem A bicycle wheel completed 155.2 revolutions as it was rolled along the boundary of a field. The wheel diameter is 2.16 ft. What is the length of the field (ft)?

Solution

$$\begin{aligned} D(\text{ft}) &= \pi \times D \times N = 3.14 \times 2.16\,\frac{\text{ft}}{\text{rev}} \times 155.2\,\text{rev} \\ &= 1052.628\ldots \text{or}\ \ 1050\ \ \text{ft} \end{aligned}$$

One advantage of odometer wheels over pacing is increased accuracy, but they still must be rolled along the surface in a straight line to measure a distance accurately. When used correctly, an error of 1 foot per 100 feet can be expected.

12.3.3 Taping/Chaining

The most accurate traditional method of measuring distances uses a steel tape, chain. The use of the term chain is a holdover from when surveyors used a chain to measure distance. When proper procedures are followed, the error will be less than 1.0 feet in 3000 feet. The standard equipment for a taping party consists of a tape, two range poles, a set of 11 chaining pins, two plumb bobs, a hand level, and a field notebook. A taping party can be as small as two people, but at least three are recommended. If the line being taped requires removing vegetation, more will be required. Each piece of taping equipment is described in the following paragraphs.

12.3.3.1 Surveyor's Chain

Chains were first used because blacksmiths could make and connect individual links to form a chain. By adding a short section of threaded rod and a handle on one or both ends, the chain could be adjusted for wear. Surveyor's chains have been replaced by steel tapes. Even though steel tapes are used instead of chains,

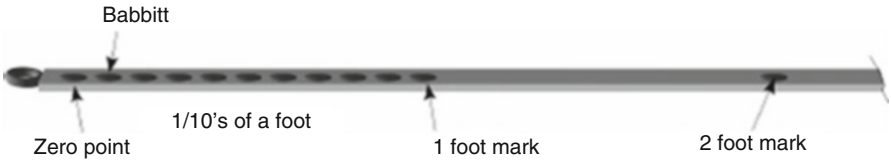

Fig. 12.3 Segment of Babbitt style tape

measuring distance using a steel tape is often called chaining. Traditionally surveyor's tapes were constructed of high-quality steel, but accurate surveyor's chains constructed of nonmetallic materials are available. The modern standard steel chain is 100 ft long and 3/8 inch wide and weighs 2–3 pounds per 100 feet. Older tapes are graduated with marks set in Babbitt-metal bosses with each foot marked, from 0 to 100 ft. Notice in Fig. 12.3 that only the first foot of the tape has graduations for measuring partial feet. For Babbitt chains, the graduations are 1/10 of a foot. It is not visible in Fig. 12.3, but the last foot, 99–100, will also be graduated. This is the common design of a Babbitt surveyor's chain.

Newer surveyor's chains eliminate the Babbitt and have the marks etched on the face of the tape. The subdivisions are usually in tenths and/or hundredths of a foot. The graduated foot may be an extended foot (Fig. 12.4) or the first foot (Fig. 12.5). A chain with the first foot graduated is called a cut chain, and a chain with the extend foot graduated is called an add chain.

These terms indicate if the partial foot is added or subtracted. This is explained in more detail in the following section. Determining the style of chain that is being used is important; otherwise it is easy to have an error of 1 foot when reading an add or cut tape incorrectly.

Another style of modern chain is called the highway chain. Highway chains are fully graduated. Because they are fully graduated, they are read directly. The user does not need to determine if it is a cut or add chain.

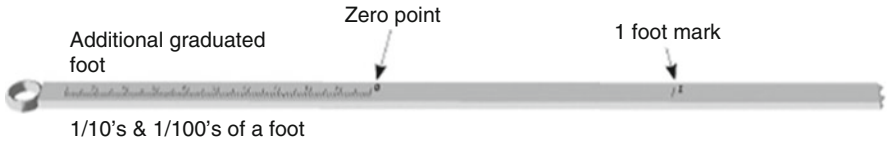

Fig. 12.4 Typical add tape

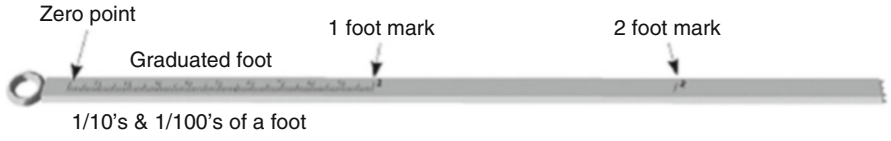

Fig. 12.5 Segment of cut tape

Metal surveyor's chains are manufactured from an alloy of steel. Steel expands and contracts with temperature; therefore, temperature adjustments must be made when measurements to 1/100 of a foot are desired. If the temperature adjustment is not stamped on the chain, contact the manufacturer, or consult a surveying textbook. It is very important to wipe down steel tapes with a clean rag after each use and lightly oil them periodically to prevent them from rusting. They are also very easy to break by bending them sharply or pulling a loop tight.

12.3.3.2 Tapes

Tapes are popular for making rough measurements or when the accuracy of a chain is not needed. Tapes are constructed from a variety of materials. They can be manufactured from metal or not metallic materials. Many nonmetallic tapes stretch slightly when tension is applied, but others are designed so they don't. Some are constructed with steel and are accurate but do not have temperature correction. These should not be used if measurements to 1/100's of a foot are required. Tapes are usually fully graduated and range in length from 25 to 200 ft.

Nonmetallic tapes are usually lighter and easier to use. They require less maintenance and are not as easily damaged by moisture. Inexpensive nonmetallic tapes will stretch under tension and therefore are not as accurate as steel chains or tapes.

12.3.3.3 Chaining Pins

Chaining pins are made of heavy gauge wire and are 12–15 inches long. They are painted red and white and sometimes have a bright cloth attached to help locate them in tall grass. They are used to mark the end of each tape length and come with 11 pins in a set. One pin is used to mark the start of the chaining (taping), and the remaining ten pins are used to mark each full length of tape. When all 11 pins have been used, assuming a 100 ft tape, 1000 ft has been measured.

12.3.3.4 Range Poles

Range poles are 1 inch diameter tubular steel or nonmetallic shafts 6–10 ft long with one pointed end. They are alternately painted red and white to make them very visible. The visibility is used to establish lines of sight and mark stations so they can be seen from a distance (Fig. 12.6).

Fig. 12.6 Range pole

12.3.3.5 Plumb Bobs

Plumb bobs with 6–10 ft of cord attached are used when measuring horizontal distances on sloping or irregular ground to transfer the distance from the horizontally held tape to the point on the ground. They also are attached to a surveyor's level to locate the vertical position over a stake when measuring distances by stadia or EDM or laying out angles (Fig. 12.7).

12.3.3.6 Hand Level

A hand level consists of a small sighting tube 5–6 inches long equipped with a spirit level, a glass tube filled with a liquid, and a bubble (Fig. 12.8). The image of the bubble is reflected by a prism and can be observed by looking through the tube. The instrument is held to the operator's eye and is leveled by raising or lowering the front end until the cross hair intersects the image of the spirit-level bubble.

Fig. 12.7 Plumb bob

Fig. 12.8 Hand level

This is a low-precision instrument used to make rough measurements of the slope and as an aid in keeping the surveyor's tape level. Newer models may also include stadia cross hairs and direct-reading angle scales.

12.3.3.7 Taping Procedures

Taping/chaining is a process used to measure distance. There are six steps involved in taping: (1) lining in, (2) applying tension, (3) plumbing, (4) marking tape lengths, (5) reading the tape, and (6) recording the distance.

Before computers and calculators, taping distances greater than 100 feet were measured by units of 100 feet called stations. A distance of 100 feet is called a full station and is written as 1 + 00 ft. Using stations, a distance of 123 feet is written as 1 + 23 ft. The modern practice is to record all distances in decimal feet.

Taping procedures can be used to measure both slope distance and horizontal distance. A slope distance results when the measurement was taken with the tape laying on the ground surface.

When taping, slope distance adhering to the following procedures will help ensure accurate results. A taping party consists of at least three people: the head chainman, the rear chainman, and a note keeper. An ax man also may be necessary in brushy areas. The 11 chaining pins serve as temporary markers for each station and also help to count the number of full stations measured.

The head chainman begins by setting a pin at the starting point and leads off with the 100 foot end of the tape and ten pins. After one full station or length of chain has been measured, the head chainman places a pin in the ground at the 100 foot mark. At this point, he or she will have nine pins left on the ring. As the chain is moved to the next station, the rear chainman does not pull the pin used to start the chaining. He only pulls the pins used at the 100 ft marks. After two full stations, the head chainman will have placed three pins in the ground and have eight pins on the ring, and the rear chainman will have one in hand and one in the ground. If this system is carefully followed, the number of full stations measured will always be the same as the number of pins held by the rear chainman.

As described above, most surveyor's tapes are graduated in feet throughout their full length, with the first and/or last foot of the tape graduated in tenths or tenths and hundredths of a foot. A different procedure is required for measuring a distance shorter than a full tape length. When the party nears the end of the line and the remaining distance is less than 100 feet, the rear chainman holds the zero mark on the last pin, and the head chainman pulls the chain taunt. The head chainman then moves the chain towards them until it aligns with the closest whole foot mark if an

add chain is used or away from them until it aligns with the closest whole foot mark if a cut chain is being used. The rear chainman takes up any slack and they both read the tape. The rear chainman's reading is subtracted from the head chainman's reading when a cut tape is used. The rear chainman's reading is added to the head chainman's reading when an add tape is used. For example, suppose that an add chain is being used and the head chainman reads 53 feet and the rear chainman reads 0.21 feet. If the rear chainman has six pins, the total length of the distance is 653.21 feet [(6 × 100) + (53 ft + 0.21 ft)]. If a cut chain was being used, the distance would be 652.79 feet [(6 × 100 ft) + (53 ft − 0.21 ft)].

The following rules, if carefully followed, will help guarantee accuracy in taping:

1. Align the tape carefully, and keep the tape on the line being measured.
2. Keep a uniform tension of 15 pounds of pull on the tape for each measurement.
3. Keep in mind the style of tape being used to avoid an error of 1 or 2 feet at each end of the tape.
4. "Break chain" on slopes as necessary, or record the percent slope if measuring with the tape on the ground.
5. Carefully mark each station and keep an accurate count of the stations.

To measure a horizontal distance, the tape must be held horizontal or additional information must be collected, so horizontal distance can be calculated. Two methods are available for measuring horizontal distance and one for determining horizontal distance by measurement and calculation. The two measuring methods are (1) tape and plumb bob and (2) electronic distance measuring (EDM). When an EDM is used, the distance is horizontal if the instrument is horizontal at the time of measurement. When the measurement and calculation method is used, the change in elevation, or vertical angle must also be measured.

The need for horizontal measurements is illustrated in Fig. 12.9. When measured along the surface of the ground, the distance is 26.1 feet, whereas the true horizontal distance is 25.00 feet.

The measure and calculate method measures slope distance and converts the slope distance to horizontal distance using the percent slope, the difference in elevation, or the vertical angle. The percent slope can be measured by a hand

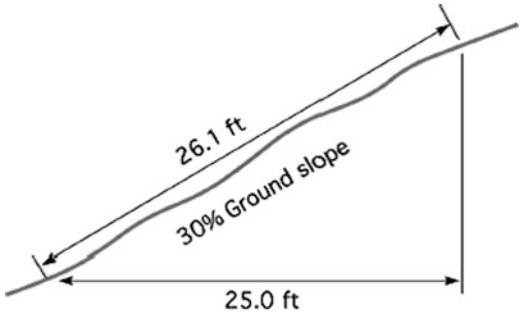

Fig. 12.9 Effect of ground slope on true horizontal distance

level or a surveying level. When the percent slope is known, the horizontal distance can be determined through the use of the slope equation and the Pythagorean theorem.

Problem Determine the horizontal distance when the slope distance is 234.5 ft and the percent slope is 3.4%.

Solution For slopes of 5% or less the difference between slope distance and horizontal distance is very small. If a small error is acceptable, the slope equation can be used. The first step is to determine the amount of change in elevation that occurs. This can be done by rearranging the slope equation for the rise:

$$\%\text{Slope} = \frac{\text{rise}}{\text{run}} \times 100$$

$$\text{rise} = \frac{\%\text{Slope} \times \text{run}}{100} = \frac{3.4 \times 234.5 \text{ ft}}{100} = 7.973 \text{ or } 8.0 \text{ ft}$$

A distance of 234.5 feet with a percent slope of 3.4% will result in a change in elevation of 7.973 feet. Note: 7.973 feet is used instead of 8.0 feet because this is the first step in a multiple step problem. The rise forms the opposite side of a right triangle, and the measured slope distance is the hypotenuse of a right triangle. The horizontal distance can be determined by rearranging Pythagorean's theorem to solve for the horizontal distance, side *b*:

$$a^2 = b^2 + c^2$$

$$b^2 = a^2 - c^2$$

$$b = \sqrt{a^2 - c^2} = \sqrt{234.5^2 - 7.973^2} = 234.36 \ldots \text{ or } 230 \text{ ft}$$

The horizontal distance is 230 feet.

If a small amount of error is not acceptable, trigonometric functions must be used. The first step is to convert percent slope to slope degrees. The equation is:

$$\text{SDeg} = \arctan \text{SP}$$

where SDeg = slope degree; arctan = trig function; SP = slope percent.

The slope degree is:

$$\text{SDeg} = \arctan 0.034 = 1.947 \ldots \text{degrees}$$

The last step is determining the horizontal distance. The equation is:

$$\text{HD} = \text{SD} \times \text{cosine SDeg}$$

where HD = horizontal distance; cosine = trig function; SDeg = slope degree.

The horizontal distance is:

$$\begin{aligned} \text{HD} &= \text{SD} \times \text{cosine SDeg} \\ &= 234.5 \text{ ft} \times \text{cosine } 1.947\ldots \\ &= 234.5 \text{ ft} \times 0.999 \\ &= 234.36\ldots \text{ or } 230 \text{ ft} \end{aligned}$$

The horizontal distance is 230 feet. Note: both methods produced the same answer. This occurred because the percent slope was a small number.

Table 12.1 can also be used to determine the horizontal distance for various slopes up to 30%. Note that for slopes up to 5%, the correction factor is less than 0.125 ft/100 ft (1.5 in/100 ft) but the correction factor increases more dramatically after 5%.

When Table 12.1 is used, the correction factor per 100 ft is multiplied by the slope distance and divided by 100, and the product is subtracted from the slope distance. It is important to remember that the correction factors are for 100 ft of distance. You must divide the measured slope distance by 100 first:

$$\text{HD} = \text{SD} - \left(\left(\frac{\text{SD}}{100} \right) \times \text{CF} \right)$$

where HD = horizontal distance; SD = slope distance; CF = correction factor.

Problem Use Table 12.1 to determine the horizontal distance (HD) when the slope distance (SD) is 623.82 ft and the slope is 12.0%.

Table 12.1 Correction factors for converting slope distance to horizontal distance

Slope	Correction factor (ft/100 ft)	True horizontal distance (100 ft)
1	0.005	99.995
2	0.020	99.980
3	0.045	99.955
4	0.080	99.920
5	0.125	99.875
6	0.180	99.820
7	0.245	99.755
8	0.321	99.679
9	0.406	99.594
10	0.501	99.499
11	0.607	99.393
12	0.723	99.277
15	1.131	98.869
18	1.633	98.367
20	2.020	97.980
25	3.175	96.825
30	4.606	95.394

Solution

$$\begin{aligned} \text{HD} &= \text{SD} - \left(\left(\frac{\text{SD}}{100} \right) \times \text{CF} \right) \\ &= 623.82 \text{ ft} - \left(\left(\frac{623.82 \text{ ft}}{100} \right) \times 0.723 \right) \\ &= 623.82 \text{ ft} - 4.5102186 = 619.309 \ldots \text{ or } 619 \text{ ft} \end{aligned}$$

The horizontal distance is 619 feet.

When the ground slope is not uniform, the percent slope and the slope distance for each segment of the line must be determined and a separate correction applied to each segment.

When method one is used, tape and plumb bob, one end of the tape is held on the ground, and the down slope end is raised until the tape is horizontal. The horizontal distance is transferred to the ground from the elevated end of the tape using a plumb bob. When the slope is more than 5%, it is necessary to use a process known as "breaking chain."

In this method, the head chainman lays out the full length of the tape. The 100 feet length then is divided into convenient increments, usually 25 or 50 ft, with the chainman holding the tape horizontal and plumbing down to the ground at each increment. This process is illustrated in Fig. 12.10. In this example, the chain was "broken" into 25 f. sections. Every 25 ft a plumb bob and line were used to set a pin.

For accurate results, a taping activity must be very carefully thought out and well organized.

12.3.4 Stadia

Measuring distance by stadia relies upon a fixed angle being designed into the instrument. "Stadia" comes from an early Greek word for a unit of length. Surveying instruments equipped for stadia measurement have two additional horizontal cross hairs, called stadia hairs. They are placed equidistant above and below the horizontal leveling cross hair (Fig. 12.11).

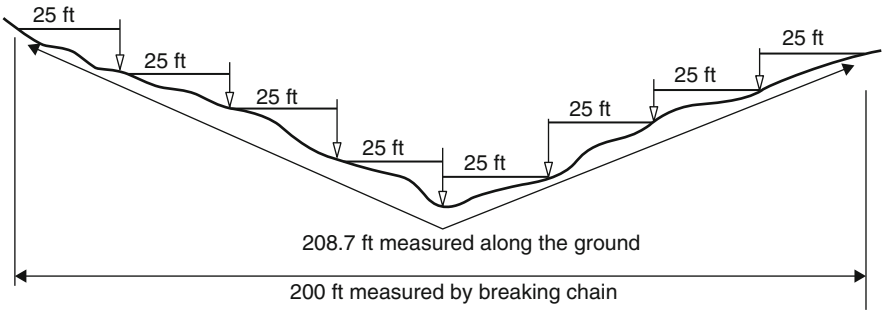

Fig. 12.10 Measuring sloping ground by breaking chain

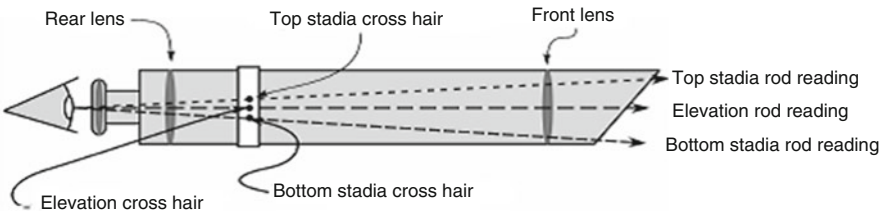

Fig. 12.11 Principles of stadia

The distance between the stadia hairs and the horizontal cross hair is fixed by the manufacturer to provide a constant stadia interval factor (SIF) for the instrument. The most common stadia interval factor is 100. Instruments that have a SIF of 100 will have a 1 foot stadia interval, that is, the difference between the top stadia reading (TSR) and the bottom stadia reading (BSR), when the rod is held 100 ft away from the instrument (Fig. 12.12).

The angle formed by reading the top and bottom cross hairs is constant; therefore, the unit of the measure is determined by the unit of measure of the rod. When a Philadelphia style rod is used without the target, the distance will be in units of feet. When a metric rod is used, the distance will be in units of meters. When the stadia method is used to measure a distance, the instrument person reads the TSR and the BSR and then multiplies the difference by the stadia interval factor, in the form of an equation:

$$D\,(\text{ft}) = (\text{TSR} - \text{BSR}) \times 100$$

Refer to Fig. 12.13. The top stadia hair reading (TSR) is 6.29, and the bottom stadia hair reading (BSR) is 3.71. Thus, the stadia interval is equal to 6.29 minus 3.71, or 2.58 ft. The distance from the instrument to the rod is equal to 2.58 multiplied by 100, or 258 ft.

Problem What is the distance to the rod if the stadia readings are TSR = 6.07 and the BSR = 3.02?

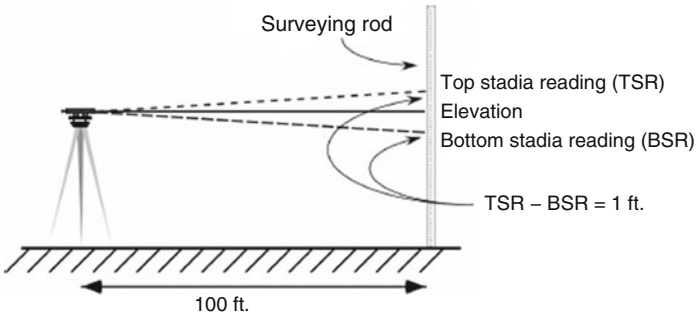

Fig. 12.12 Measuring distance by stadia

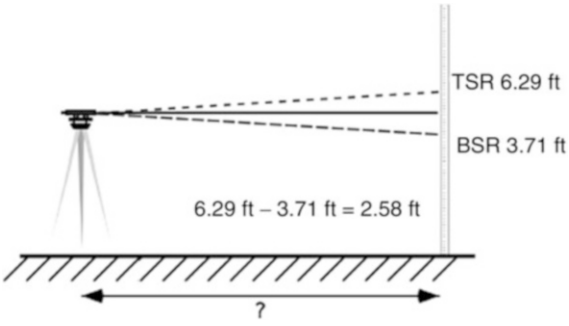

Fig. 12.13 Example using stadia

Solution

$$D\ (\text{ft}) = (\text{TSR} - \text{BSR}) \times 100 = (6.07\text{ft} - 3.02\text{ft}) \times 100 = 305\text{ft}$$

12.3.5 Optical Range Finders

Many different technologies are used with optical range finders. One simple type of instrument operates on the function of triangles. When the operator looks through the eyepiece, when the instrument is not set for the distance, they see two identical images that are blurry. The operator adjusts the focus until two images are in coincidence, superimposed on top of each other. The distance is read from a scale on the instrument. Optical range finders have an acceptable level of accuracy for reconnaissance or sketching purposes for short distances, but the error increases as the distance increases.

12.3.6 Electronic Distance Measurement (EDM)

EDM instruments determine lengths based on the time that it takes for an energy wave to travel from one end of a line to the other and return. They have replaced the difficult and painstaking task of taping for accurate measurement of horizontal distances. They also can measure distance over bodies of water or other inaccessible terrains as long as they have a clear line of sight. Some types require a reflective surface to bounce the beam back, while some are reflector less (Fig. 12.14). Others use a second unit to return the signal. Distance is determined by rearranging the velocity equation:

$$V\left(\frac{\text{ft}}{\text{min}}\right) = \frac{\text{Distance (ft)}}{\text{Time (min)}}$$

$$\text{Distance} = V\left(\frac{\text{ft}}{\text{min}}\right) \times \text{Time (min)}$$

A big advantage of EDMs is that the operator does not need to walk the distance; all they need is a line of sight. They can also be used when the line of sight is obscured by fog, light rain, or even vegetation if it is not dense.

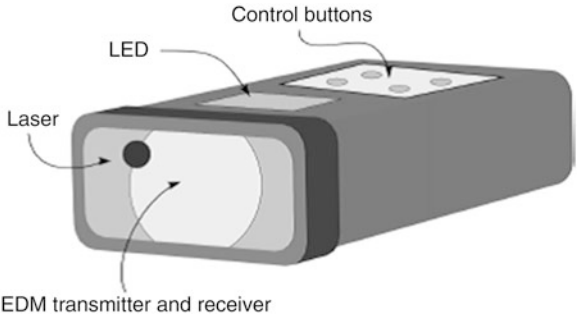

Fig. 12.14 An example of an EDM

12.4 Calibration Procedure

Measuring instruments are mechanical/electrical devices. Their accuracy will sometimes change with use and is guaranteed to change with abuse. Checking the accuracy of instruments is called calibration. Instruments are calibrated by checking their performance against a standard. The difference in length between the averaged measurements and the standard is known as error. This error can be a random error or a systematic error. Random error is unpredictable and must be controlled by following recommended techniques and procedures. Systematic errors are usually caused by damage or wear to the instrument. If the calibration process indicates a systematic error, an error that is constant with each measurement, then a correction factor can be calculated so that each measurement taken with the instrument can be corrected. An example of a systematic error is the change in a steel tape cause by temperature.

12.4.1 Determining Correction Factor

During the measurement of a known 50.0 ft distance with an odometer wheel, measurements of 49.9, 49.8, and 49.7 ft were recorded. What is the correction factor?

Solution The first step is to determine the average distance:

$$(49.8 + 49.8 + 49.7)/3 = 49.8 \text{ Ft}$$

$$\text{CF}\left(\frac{\text{ft}}{\text{ft}}\right) = \frac{\text{Known distance} - \text{Measurement}}{\text{Known distance}}$$

$$= \frac{50.0\text{ ft} - 49.8\text{ ft}}{50\text{ ft}} = 0.004\ \frac{\text{ft of error}}{\text{ft of distance}}$$

The instrument measurements will be 0.004 feet short for every foot of distance it measures. Once the correction factor is determined, it can be used to adjust each of the measurements for the error in the equipment. The equation is:

$$D_c = \text{Measured distance} + (\text{measured distance} \times \text{correction factor})$$

Problem Determine the corrected distance for a measured distance of 150.5 ft when the instrument has an error of 0.004 ft/ft.

Solution

$$\begin{aligned} D_c &= 150.5 \text{ ft} + \left(150.5 \text{ ft} \times 0.004 \frac{\text{ft}}{\text{ft}}\right) \\ &= 150.5 \text{ ft} + 0.602 = 151.103 = 151.1 \text{ ft} \end{aligned}$$

The corrected distance is 151.1 ft.

Problem Determine the corrected distance for a measured distance of 245.5 ft when the instrument has an error of −0.02 ft/ft.

Solution

$$\begin{aligned} D_c &= 245.5 \text{ ft} + \left(245.5 \text{ ft} \times \left(-0.02 \frac{\text{ft}}{\text{ft}}\right)\right) \\ &= 245.5 + (-4.91) = 240.59 \text{ or } 240 \text{ ft} \end{aligned}$$

12.5 Metric Problems

Problem Determine the pace factor for an individual that counted 132, 134, and 133 paces for a distance of 100 m.

Solution

$$\text{PF} = \frac{\text{Distance}}{\text{Paces}} = \frac{100 \text{ m}}{\frac{133 + 134 + 132}{3}} = \frac{100 \text{ m}}{133 \text{ paces}} = 0.7518 \text{ or } 0.75 \frac{\text{m}}{\text{pace}}$$

Problem An individual with a pace factor of 0.65 m/pace counts 380 paces for an unknown distance. What is the distance?

Solution

$$\begin{aligned} D &= \text{PF} \times P \\ &= 0.65 \frac{\text{m}}{\text{pace}} \times 380 \text{ paces} = 247 \text{ m} \end{aligned}$$

Problem A wheel with a diameter of 70 cm is used to measure a distance by rolling it along the ground. It was rolled 124 revolutions. What is the distance?

$$D = \frac{\pi \times \text{dia}}{\text{revolution}} \times \text{revolutions}$$
$$= \frac{\pi \times 70\text{ cm}}{1\text{ rev}} \times 124\text{ rev} \times \frac{1\text{ m}}{100\text{ cm}} = 272.69\ldots \text{or } 273\text{ m}$$

Problem Use Table 12.2 to determine the horizontal distance (HD) when the slope distance (SD) is 350 m and the slope is 12.0%.

Solution

$$\text{HD} = \text{SD} - \left(\left(\frac{\text{SD}}{100}\right) \times \text{CF}\right)$$
$$= 350\text{ m} - \left(\left(\frac{350\text{ m}}{100}\right) \times 0.72\right) = 350\text{ m} - 2.52 = 347.48 \text{ or } 34.7\text{ m}$$

Table 12.2 Correction factors for converting slope distance to horizontal distance

Slope	Correction factor (m/100 m)	True horizontal distance (100 m)
1	0.01	99.99
2	0.02	99.98
3	0.05	99.95
4	0.08	99.92
5	0.13	99.87
6	0.18	99.82
7	0.25	99.75
8	0.32	99.68
9	0.41	99.59
10	0.50	99.50
11	0.61	99.39
12	0.72	99.28
13	1.13	99.15
14	1.63	99.02
15	1.13	98.87
18	1.63	98.37
25	3.18	96.82
30	4.61	95.39

Problem Determine the horizontal distance when the stadia method is used with a metric rod. The top stadia reading is 1.23 m, and the bottom stadia reading is 0.82 m.

Solution

$$D\,(\mathrm{m}) = (\mathrm{TSR} - \mathrm{BSR}) \times 100$$
$$= (1.23 - 0.82) \times 100 = 0.41 \times 100 = 41\ \mathrm{m}$$

Problem Determine the corrected distance for a measured distance of 750.5 m when the instrument measured distances are of 49.8, 49.8, 49.7 and 49.8 meters for a standard distance of 50 m.

Solution The first step is to determine the correction factor. Before determining the correction factor, the average measurement must be calculated:

$$\mathrm{Distance} = \frac{49.8 + 49.8 + 49.7 + 49.8}{4} = 49.775\ \mathrm{m}$$

$$\mathrm{CF}\left(\frac{\mathrm{m}}{\mathrm{m}}\right) = \frac{\mathrm{known\ \ distance} - \mathrm{Measurement}}{\mathrm{Known\ \ distance}}$$
$$= \frac{50.0\ \mathrm{m} - 49.775\ \mathrm{m}}{50\ \mathrm{m}} = 0.0045\ \frac{\mathrm{m\ \ of\ \ error}}{\mathrm{m\ \ of\ \ distance}}$$

The last step is to use the correction factor to determine the corrected distance:

$$\mathrm{Distance} = \mathrm{Measurement} + \mathrm{Correction}$$
$$= 750.5\ \mathrm{m} + \left(750.0\ \mathrm{m} \times 0.0045\,\frac{\mathrm{m}}{\mathrm{m}}\right)$$
$$= 750.5\ \mathrm{m} + 3.375\ \mathrm{m} = 753.875 \text{ or } 735.9\ \mathrm{m}$$

Chapter 13
Angles and Areas

13.1 Objectives

1. Be able to use three indirect methods to lay out and/or measure angles.
2. Be able to find the area of standard geometric shapes.
3. Be able to determine the area of irregular-shaped tracts of land by division into standard geometric shapes.
4. Be able to determine the area of irregular-shaped tracts of land using two trapezoidal equations.

13.2 Introduction

The ability to lay out and measure angles is an important skill of agricultural surveying. In this section, you will learn, using simple tools and procedures, three indirect methods that can be used to lay out a perpendicular (90°) angle and one method that can be used to lay out or measure any angle between 0° and 90°. These procedures are useful in planning buildings and fences or determining the corner angles of irregular-shaped tracts, fields, and/or smaller areas.

Knowing the area of buildings and fields is important knowledge when managing agricultural enterprises. This chapter will illustrate the equations used for determining the area of standard geometric shapes and methods that can be used to determine the area of irregular-shaped fields.

13.3 Angles

Surveyors label the three parts of an angle as the backsight (base line), the foresight, and the vertex, where the backsight and foresight intersect. Angles can be measured or laid out using instruments, direct method, or by measuring, indirect method. The measurement and laying out of angles using instruments are included in the chapter on surveying. This section will include three common indirect methods for measuring or laying out an angle. Two of these are limited to 90° angles, the chord

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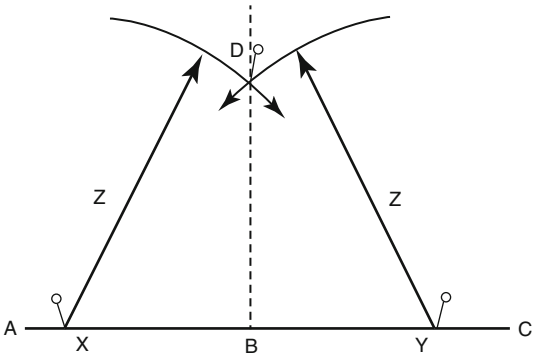

Fig. 13.1 Laying out a right angle by the chord method

method and the 3-4-5 method, and the third, tape-sine, can be used with any angle between 0° and 90°. The following discussion illustrates all three methods.

13.3.1 Chord Method

A chord is a line connecting any two points on a circle. This geometric principle can be used to lay out a line at a 90° angle to a base line. This method is very simple and can be accomplished with two different lengths of string or even tree branches. The one disadvantage is that the base line must be extended past the turning point (*B*). This method is illustrated in Fig. 13.1.

The line *BD* is established at a 90° angle from line *AC* by completing the following steps:

1. Establish the base line *AC* if it is not in existence (fence or road edge, etc.).
2. Establish the vertex at *B*.
3. Set points *X* and *Y* equidistant from point *B* and on line *AC*.
4. Use a length greater than the distance *XB* or *YB* for *Z*, and scribe an arc from *X* and *Y* as shown.
5. Set a stake at the intersection of the two arcs (*D*).
6. The line established by this stake and *B* will be at 90° with the base line *AC*.

This method is simple in principle but not easy to complete because of the difficulty in marking the arcs. On tilled ground they can be formed by marking the surface, but when working on grass or taller vegetation, it is much more difficult. An alternative is to use two tape measures. Attach one at *X* and the other at *Y*. Any point where both tapes have the same reading will be on a 90° angle from point *B* on the base line.

13.3.2 3-4-5 Method

The 3-4-5 method of laying out a right angle is based on the Pythagorean Theorem: for any right triangle, the square of the hypotenuse is equal to the sum of the squares of the other two sides. In this method any multiples of 3 and 4 used as the sides of a

right triangle will result in the hypotenuse being a multiple of 5. To prove this, study the following equation:

$$\begin{aligned} 5 &= \sqrt{3^2 + 4^2} \\ &= \sqrt{25} \\ 5 &= 5 \end{aligned}$$

shown graphically (Fig. 13.2).

This method has three requirements: (1) the same units (feet, yards, etc.) must be used on all three sides; (2) the same multiples of 3, 4, and 5 are used for the lengths of the three sides; and (3) the longest length is used for the hypotenuse. When these three requirements are met, a 90° angle will be established.

When using the 3-4-5 method to lay out a right angle, the easiest way is to use three people and two tape measures. When two tapes are used, either the 3 or the 4, dimension is used as the base line. Mark the two corners on the base line. One person stands on each corner with a tape measure. The third person moves in the direction of the desired third corner and moves around until the two tapes cross at the correct dimensions. For example, a base line is established 8 feet long. One person holds the end of a tape, and the third person takes the tapes and moves in the direction of the desired third point until the 6-foot mark on one tape aligns with the 10-foot mark of the second tape. This point will establish a 90° corner with the person holding the 6-foot tape.

This process also may be accomplished by using a 100 ft tape. Because surveyor's steel tapes are not designed to be bent at a sharp angle, loops must be formed at two of the corners. It is recommended that at least a 5 ft. loop be used. Study Fig. 13.3.

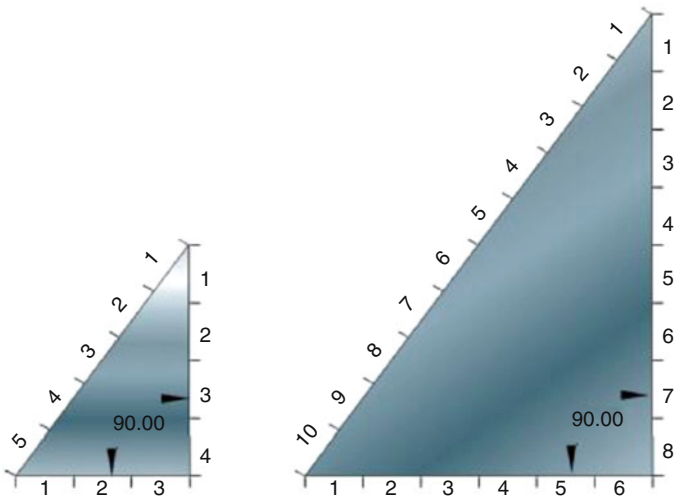

Fig. 13.2 Principles of right triangles

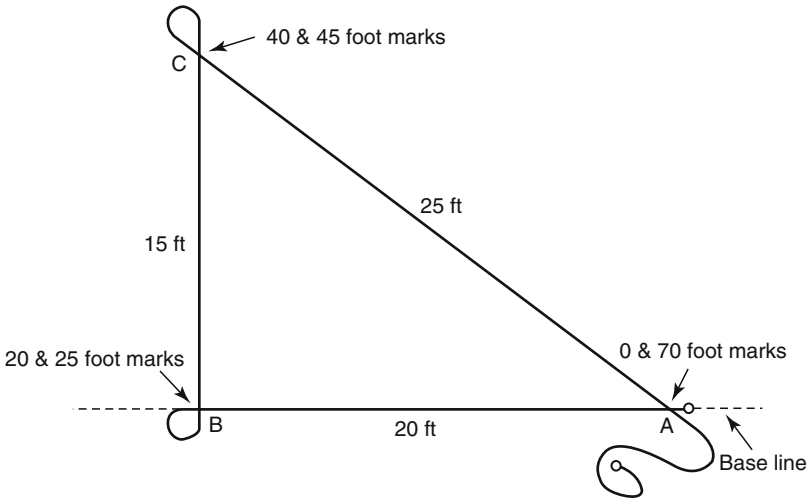

Fig. 13.3 Laying out a right angle by the 3-4-5 method using a 100 ft tape

By completing the following steps, a 90° angle will be laid out using the 3-4-5 method and a 100-foot tape. This procedure will require three people:

1. Identify the base line (*AB*) and establish corner *A*.
2. Lay out the tape along the base line with the 20 ft. mark (4 × 5 ft) at corner *B* and the zero mark at corner *A*.
3. Form a 5 ft. loop in the tape, and have a person hold the 20 ft. mark over the 25 ft. mark, and align these marks over corner *B*.
4. Lay out the remaining tape in the direction of corner *C*.
5. At corner *C* the person holds the 40-foot mark, 25 + 15 (3 x 5 ft), and forms a 5 foot loop resulting in aligning the 40-foot and 45-foot mark on the tape. Hold the 40 and 45 ft marks on corner *C*.
6. Extend the tape back to corner *A*.
7. At corner *A* the person holds the 70-foot, 45 + 25, (5 x 5 ft) and the zero mark together.
8. If the individuals at *A* and *B* hold their positions carefully on the base line, while the individual at *C* tightens the tape in both directions, a 90° angle will be made at *B*.

This process will work for any combination of lengths as long as they are multiples of 3, 4, and 5. One advantage of this method is that the base line does not need to extend past the 90° corner.

13.3.3 Tape-Sine Method

The tape-sine method uses a combination of distances measured by a tape and the sine trigonometric function. This method is not limited to 90° and can be used to lay out an angle or measure an existing angle. A review of the three commonly used trigonometric functions will make this method clear.

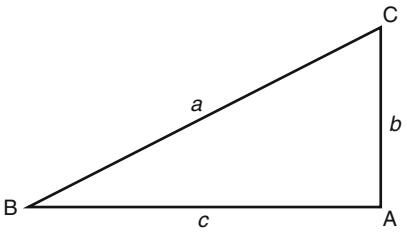

Fig. 13.4 Notation for right triangle

Trigonometric functions are based on the principle that one unique ratio exists between the lengths of any two sides for angles *B* and *C* (Fig. 13.4). Because a right triangle has three sides, each angle (*B* and *C*) has six possible ratios of two sides. Each of these combinations has been given a name. The three common ratios are:

$$\text{Sine B} = \frac{\text{Length of opposite side } (b)}{\text{Length of hypotenuse } (a)}$$

$$\text{Cosine B} = \frac{\text{Length adjacent side } (c)}{\text{Length of hypotenuse } (a)}$$

$$\text{Tangent B} = \frac{\text{Length opposite side } (b)}{\text{Length adjacent side } (c)}$$

The same relationships are true for angle *C*. Each of these functions forms an equation with three variables—the function of the angle and the lengths of two sides. If any two of the variables are known, the third can be determined.

In the tape-sine method, only the sine function is used. The procedure for laying out an angle (ϕ) is slightly different from the procedure for measuring an existing angle. The procedure for measuring an existing angle will be explained first.

Using the example illustrated in Fig. 13.5, the task is to determine the angle formed by *BAC*. The first step is to mark an equal distance along each side *AB* and *AC*. The next step is to measure the distance *BC*. This provides all the information needed to determine the angle, but this example is extended to illustrate why the method works. Form two right triangles by drawing a line from corner *A* to the midpoint of line *BC*.

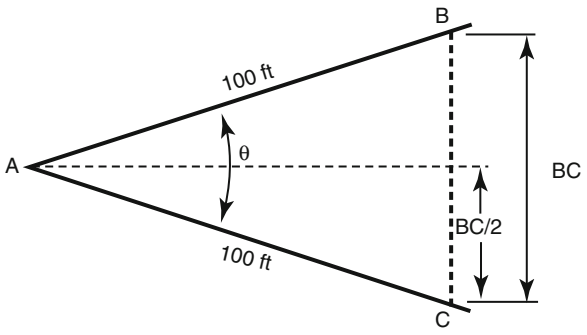

Fig. 13.5 Example of tape-sine method

The distance $BC/2$ and AC are two sides of a right triangle. For this example we will assume that the distance $BC = 61.8$ ft. The angle for either triangle can be found by using the sine equation:

$$\text{Sine A} = \frac{\text{Length of opposite side } (b)}{\text{Length of hypotenuse } (a)}$$

$$= \frac{\text{Distance BC}/2}{\text{Distance AC}} = \frac{30.9\,\text{ft}}{100\,\text{ft}} = 0.309$$

The value 0.309 is the sine ratio of angle A. The next step is to determine the angle having a sine ratio of 0.309.

To determine the angle using a calculator, enter 0.309 and the inverse of the sine function. The angle can also be determined by consulting Table 13.1.

Table 13.1 Sine values

Angle 0°	Sine of the angle	Angle 0°	Sine of the angle	Angle 0°	Sine of the angle
0	0.000	31	0.515	61	0.875
1	0.017	32	0.530	62	0.883
2	0.035	33	0.545	63	0.891
3	0.052	34	0.559	64	0.899
4	0.070	35	0.574	65	0.906
5	0.087	36	0.588	66	0.914
6	0.105	37	0.602	67	0.921
7	0.122	38	0.616	68	0.927
8	0.139	39	0.629	69	0.934
9	0.156	40	0.643	70	0.940
10	0.174	41	0.656	71	0.946
11	0.191	42	0.669	72	0.951
12	0.208	43	0.682	73	0.956
13	0.225	44	0.695	74	0.961
14	0.242	45	0.707	75	0.966
15	0.259	46	0.719	76	0.971
16	0.276	47	0.731	77	0.974
17	0.292	48	0.743	78	0.978
18	0.309	49	0.755	79	0.982
19	0.326	50	0.766	80	0.985
20	0.342	51	0.777	81	0.988
21	0.358	52	0.788	82	0.990
22	0.375	53	0.799	83	0.993
23	0.391	54	0.809	84	0.995
24	0.407	55	0.819	85	0.996
25	0.423	56	0.829	86	0.998
26	0.438	57	0.839	87	0.999
27	0.454	58	0.848	88	0.999
28	0.469	59	0.857	89	1.000
29	0.485	60	0.866	90	1.000
30	0.500				

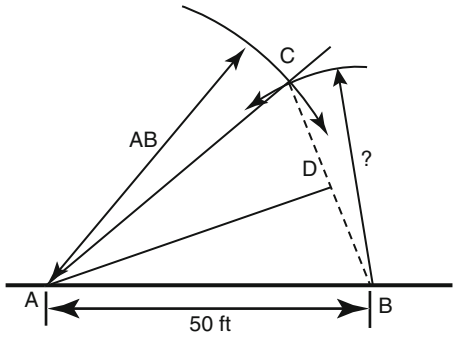

Fig. 13.6 Laying out an angle by the tape-sine method

Either source should give an angle of 18°. Remember the distance *BC*/2 was used to solve for the angle. The angle *CAB* is actually 18° × 2 or 36°.

The same method can be used to lay out an angle. Suppose you need to establish a fence at 40° to an existing fence. How would the tape-sine method be used? Study Fig. 13.6.

The principles involved are basic trigonometry. It takes two points to establish a line. To locate a point requires three distances or an angle and one distance. The desire is to establish point *C* in Fig. 13.6. In this example three distances are used. Two of the distances are identical. These are the distances *AB* and *AC*. This distance is selected by the person laying out the angle. In this example 50 ft is used. The third distance is the distance is measured from point *B* to point *C*. To determine this distance mentally, split the triangle *CAB* into two right triangles (*BAD* and *CAD*), solve for the length of the opposite side of either, and then double this distance to determine the distance *BC*. Start by using point *B* and the calculated length *BC*, and scribe a short arc in the vicinity of point *C*. Using point *A* and the length *AB*, scribe an arc that intersects the arc established at point *B*. The intersection of the two arcs is point *C*. A line from point *A* through *C* will establish the fence at the correct angle.

To determine the distance *BC*/2, the sine trigonometric function is rearranged to solve for the length of the opposite side:

$$\begin{aligned}\text{Sine A} &= \frac{\text{Opposite}}{\text{Hypotenuse}}\\ \text{Opposite} &= \text{Sine A} \times \text{Hypotenuse}\\ &= \text{Sine } 20^{\text{o}} \times 50.0\ \text{ft}\\ &= 0.3420\ldots \times 50.0\ \text{ft}\\ &= 17.1010\ldots\ \text{ft}\end{aligned}$$

The length of the *BD* or *CD* is 17.1010. . . feet. The distance *BC* is this value times two:

$$\text{BC} = 17.1010\ldots \times 2 = 34.2020\ldots \text{ or } 34.2\ \text{ft}$$

To lay out the angle, mark an arc with a radius of 34.2 feet from point *B* and another arc with a radius of 50 feet from point *A*, and set a pin at the intersection of the two arcs. This is point *C*. A line drawn from point *A* through point *C* will

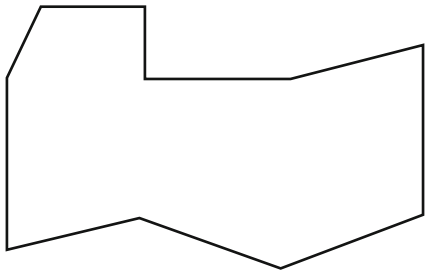

Fig. 13.7 Irregular-shaped field

establish a line at a 40° angle to the base line (*AB*). In this method, the marking of two arcs could also be eliminated by using two tape measures.

13.4 Areas of Standard Geometric Shapes

One of the most common applications of surveying is to measure the area of a lot, field, farm, or ranch. When a high level of accuracy is required, a professional engineer or a land surveyor should be employed. If this level of accuracy is not required, many areas can be determined with nothing more elaborate than a steel tape and the application of area formulas from geometry. The area of an irregularly shaped field can be found by subdividing it into standard geometric shapes, determining the areas of the subdivisions by calculation, and summing the areas of the subdivisions. For example, consider Fig. 13.7.

There is no right or wrong way to divide the field. The goal is to collect the required measurements with the expenditure of the least amount of resources. The best way will depend on the equipment used and the obstacles that exist in the field.

Figure 13.8 shows two different ways to divide the irregular-shaped field in Fig. 13.7 into standard shapes. Either method will determine the area. Method B could take less time and resources because it will require fewer measurements, but if an obstruction such as trees, swamp, building, etc. interferes with any measurements, division A would be better. To use this method it is necessary to determine and collect the necessary measurements and apply the correct area formula for each common geometric shape. The next section will review the common shapes and the area formula for each.

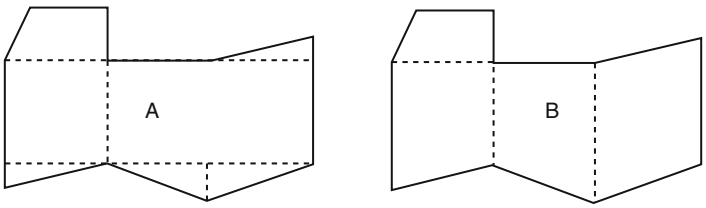

Fig. 13.8 Two alternatives for dividing irregular-shaped field into standard shapes

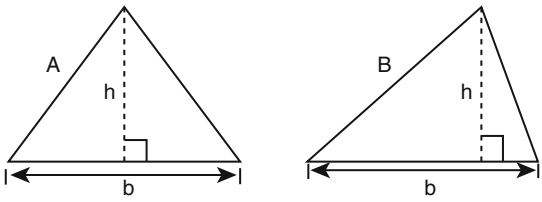

Fig. 13.9 Triangle area with base and height known

13.5 Triangle

Three different equations can be used to determine the area of a triangle, depending on the known dimensions of the triangle. These equations work if the base and height are known, the length of three sides are known or the length of two sides and one angle are known. These three equations will be explained in the next sections.

13.5.1 Base and Height

Study Fig. 13.9. In this illustration the length of the base and the length of the height are known.

This is the easiest equation to use when calculating the area of a triangle, but it contains a challenge for collecting the required dimensions. The difficulty is determining the height. The height must be measured at the point where a line at 90° to the base line passes through the opposite corner of the triangle. If the triangle is equilateral (*A*), or an isosceles triangle, the problem is not as difficult because the intersection is one half of the distance of the base line. When the triangle is not an equilateral or isosceles triangle, the intersection is much more difficult to determine. The equation for both types of triangles is:

$$A = \frac{1}{2} \times b \times h$$

where A = Area; b = Length of base; h = Height perpendicular to base.

Problem What is the area of a triangle (ac) with a base 150.0 ft long and a height of 100.0 ft.

Solution

$$A = \frac{1}{2} \times 150.0 \text{ ft} \times 100.0 \text{ ft} = 7500 \text{ ft}^2$$

$$A_{\text{acre}} = \frac{1 \text{ ac}}{43{,}560 \text{ ft}^2} \times 7500 \text{ ft}^2 = 0.17217 \ldots \text{ or } 0.1722 \text{ ac}$$

The area of the triangle is 0.1722 acres.

13.5.2 Three Sides

The second area equation is for situations where the lengths of the three sides are known (Fig. 13.10). This method for determining the area of a triangle is easier to

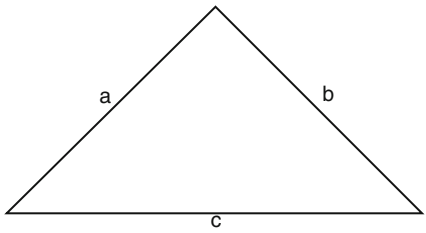

Fig. 13.10 Triangle area with three sides known

use because the only measurements are the three sides of the triangle. The shape of the triangle doesn't influence the difficulty in completing the measurements.

The primary limitation of this method is the requirement of measuring the length of all three sides. This method cannot be used if one or more of the side lengths cannot be measured. The equation for area is:

$$\mathrm{A} = \sqrt{S(S-a)(S-b)(S-c)} \qquad S = \frac{a+b+c}{2}$$

where A = area; a, b and c = lengths of the three sides; S = calculated constant.

Problem Determine the area (ft^2) for a triangle having sides measuring 650.0 ft, 428.0 ft, and 282.0 ft.

Solution First solve for S:

$$S = \frac{a+b+c}{2} = \frac{650.0\,\text{ft} + 428.0\,\text{ft} + 282.0\,\text{ft}}{2} = 680.0$$

Next solve for the area:

$$\begin{aligned} A &= \sqrt{680.0\,(680.0-650.0)\,(680.0-428.0)\,(680.0-282.0)} \\ &= \sqrt{680.0\,(30.0)\,(252.0)\,(398.0)} \\ &= \sqrt{2{,}046{,}038{,}400} \\ &= 45{,}233.15598 \text{ or } 45{,}230\,\text{ft}^2 \end{aligned}$$

The area of the triangle is 45,230 square feet.

13.6 One Angle and Two Sides

The third equation for area is used when one angle and the length of the two adjacent sides are known (Fig. 13.11).

One advantage of this method is that the length of the side opposite the known angle doesn't need to be measured. The limitations on this method are that the angle must be less than 90° and the at least one angle must be known or measured. The equation for area (A) is:

$$A = \frac{1}{2} \times b \times c \times \text{ sine } \theta$$

where A = Area; b = Known side; c = Known side; ϕ = Angle between sides b and c; sine = Sine trigonometric function.

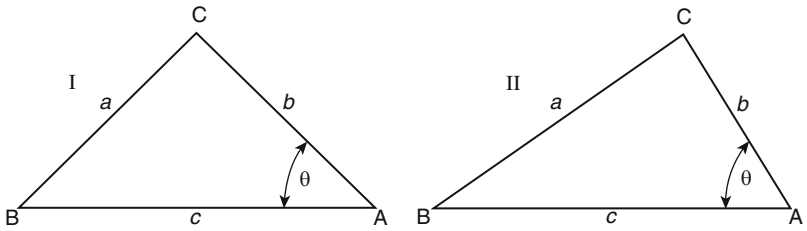

Fig. 13.11 Triangle with one angle and the adjacent sides known

Problem Determine the area (ft^2) of a triangle with sides of 350.0 ft and 555.0 ft and an included angle of 45°.

Solution

$$A = \frac{1}{2} \times a \times b \times \text{sine } \theta = \frac{1}{2} \times 350.0\,\text{ft} \times 555.0\,\text{ft} \times 0.7071\ldots$$

$$= \frac{137{,}355.4922\ldots}{2} = 68{,}677.746\ldots \text{ or } 68{,}680\,\text{ft}^2$$

The area of the triangle is 68,680 square feet.

13.7 Rectangle, Square, and Parallelogram

These three shapes are considered together because their areas are calculated using the same equation. The equation for area is:

$$A = b \times h$$

where A = Area; b = Length of base; h = Height perpendicular to base.

Remember that the height (h) for a parallelogram is perpendicular to the base (b); see Fig. 13.12.

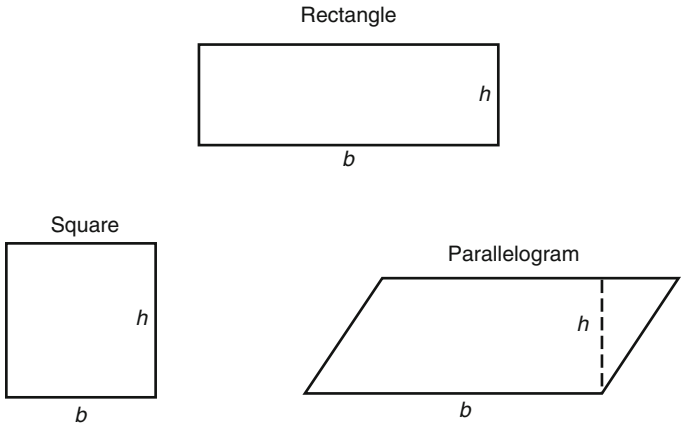

Fig. 13.12 Base and height for rectangles, squares, and parallelograms

Problem What is the area (ft^2) of a rectangle measuring 1320.0 ft by 660.0 ft?

Solution

$$A = b \times h = 1{,}320.0 \text{ ft} \times 660.0 \text{ ft} = 871{,}200 \text{ ft}^2$$

The area of the rectangle is 871,200 square feet.

Problem What is the area (ac) of a parallelogram when the base measures 1050.0 ft and the height measures 750.0 ft?

Solution The area equation is used, and then the square feet converted to acres or the acres conversion can be added to the area equation:

$$\begin{aligned} A\,(\text{ac}) &= b \times h \times \frac{1\,\text{ac}}{43{,}560\,\text{ft}^2} \\ &= 1050.0\,\text{ft} \times 750.0\,\text{ft} \times \frac{1\,\text{ac}}{43{,}560\,\text{ft}^2} \\ &= 18.078\ldots \text{or } 18.08\,\text{ac} \end{aligned}$$

The area of the parallelogram is 18.08 acres.

13.8 Circle or Sector

The area of a circle, in a slightly different form, was used in Chap. 5 in figuring engine displacement:

$$A = \pi\ r^2$$

where A = Area; $\pi = 3.14$; r = Radius of the circle.

A sector is slice of a circle. Two equations are available for determining the area of a sector. The equation used is determined by which dimensions are known, the angle or the arc length. Study Fig. 13.13.

When the angle of the sector is known the equation is:

$$A = \frac{\pi \times r^2 \times \theta}{360}$$

where A = Area; $\pi = 3.14$; θ = Included angle of the sector; r = Radius of sector.

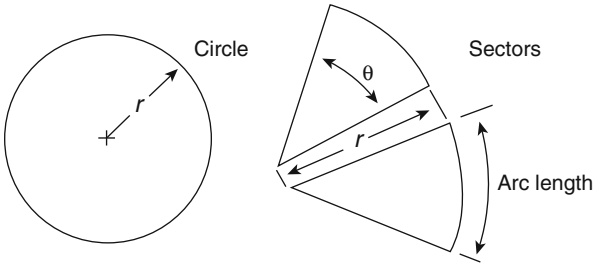

Fig. 13.13 Circle and sectors

When the length of the arc is known, the equation for a sector is:

$$A = \frac{r \times \text{arc length}}{2}$$

Problem Find the area of a circle (ft^2) having a radius of 75.0 ft.

Solution

$$A = \pi \times r^2 = 3.14 \times (75.0 \text{ ft})^2 = 17{,}662.5 \text{ or } 17{,}700 \text{ ft}^2$$

The area of the circle is 17,700 square feet.

Problem Find the area of a sector (ft^2) with a radius of 135.0 ft and an angle of 60.0°.

Solution

$$A = \frac{\pi \times r^2 \times \theta}{360} = \frac{3.14 \times (135.0 \text{ ft})^2 \times 60.0^\circ}{360}$$
$$= \frac{3{,}433{,}590}{360} = 9537.75 \text{ or } 9540 \text{ ft}^2$$

The area of the sector is 9540 square feet.

Problem What is the area of a sector (ac) if the radius is 100.0 ft and the arc length is 210.0 ft?

Solution (Adding the conversion value from square feet to acres):

$$A = \frac{r \times \text{arc length}}{2} \times \frac{1 \text{ ac}}{43{,}560 \text{ ft}^2}$$
$$= \frac{100.0 \text{ ft} \times 210.0 \text{ ft}}{2} \times \frac{1 \text{ ac}}{43{,}560 \text{ ft}^2}$$
$$= \frac{21{,}000}{87{,}120} = 0.24104 \ldots \text{ or } 0.241 \text{ ac}$$

13.9 Trapezoid

A trapezoid is a four-sided figure with only two parallel sides. Two shapes meet this definition (Fig. 13.14). Note that the height must be measured perpendicular to the parallel sides.

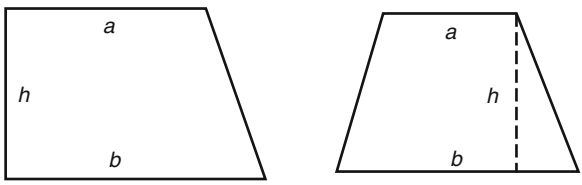

Fig. 13.14 Two types of trapezoids

The area of both types of trapezoids is determined by the equation:

$$A = h \times \left(\frac{a+b}{2}\right)$$

where A = Area; h = Height (distance between the parallel sides); a = Length of one parallel side; b = Length of the second parallel side.

Problem What is the area (ac) of a trapezoid with parallel sides of 300.0 ft and 450.0 ft and with a height of 120.0 ft?

Solution (Including conversion to acres):

$$\begin{aligned} A &= h \times \left(\frac{a+b}{2}\right) \times \frac{1\,ac}{43{,}560\,\text{ft}^2} \\ &= 120.0\text{ ft} \times \left(\frac{300.00\,\text{ft} + 450.00\,\text{ft}}{2}\right) \times \frac{1\,ac}{43.560\,\text{ft}^2} \\ &= 45{,}000\text{ ft}^2 \times \frac{1\,ac}{43{,}560\,\text{ft}^2} \\ &= 1.03305\ldots \text{ or } 1.033\,ac \end{aligned}$$

The area of the trapezoid is 1.033 acres.

13.10 Determining Areas of Irregular-Shaped Fields Using Standard Geometric Shapes

Very few agricultural fields or lawns are standard geometric shapes. They may not be as complicated as the field illustrated in Fig. 13.15, but the principles for determining area are the same. The total area is the sum of each individual area.

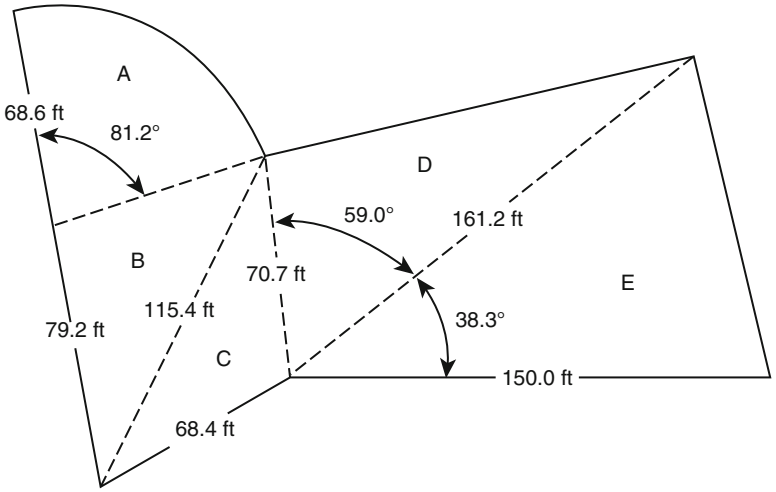

Fig. 13.15 Example of determining the area of an irregular shape

The key to efficient calculations is dividing the irregular shape into the fewest possible number of standard shapes.

Problem Determine the number of acres for the field illustrated in Fig. 13.15.

Solution Shape *A* is a sector of a circle with a known radius and angle. The area of this shape can be found by using the sector equation:

$$A_{\mathrm{A}} = \frac{\pi \times r^2 \times \theta}{360} = \frac{\pi \times 68.6\,\mathrm{ft} \times 81.2}{360}$$
$$= \frac{12{,}004{,}778}{360} = 3334.66\ldots \text{ or } 3330\,\mathrm{ft}^2$$

Shape *B* is a triangle with the length of the sides known:

$$A_{\mathrm{B}} = \sqrt{S(S-a)(S-b)(S-c)} \quad S = \frac{a+b+c}{2}$$
$$S = \frac{a+b+c}{2} = \frac{68.6\,\mathrm{ft} + 79.2\,\mathrm{ft} + 115.4\,\mathrm{ft}}{2} = \frac{263.2}{2} = 131.6$$

$$A_{\mathrm{B}} = \sqrt{S(S-a)(S-b)(S-c)}$$
$$= \sqrt{131.6(131.6-68.6)\,(131.6-79.2)\,(131.6-115.4)}$$
$$= \sqrt{131.6(63)\,(52.4)\,(16.2)} = \sqrt{7{,}037{,}894.304} = 2652.90\ldots \text{ or } 2{,}650\ \mathrm{ft}^2$$

Shape *C* is another triangle with the lengths of all three sides known:

$$A = \sqrt{S(S-a)(S-b)(S-c)} \quad S = \frac{a+b+c}{2}$$
$$S = \frac{a+b+c}{2} = \frac{68.4\,\mathrm{ft} + 70.7\,\mathrm{ft} + 115.4\,\mathrm{ft}}{2} = \frac{254.5}{2} = 127.25$$

$$A = \sqrt{S(S-a)(S-b)(S-c)}$$
$$= \sqrt{127.25(127.25-68.4)\,(127.25-70.7)\,(127.25-115.4)}$$
$$= \sqrt{127.25(58.85)\,(56.55)(11.85)} = \sqrt{5{,}018{,}283.793}$$
$$= 2240.15\ldots \text{ or } 2{,}240\ \mathrm{ft}^2$$

Area *D* is a triangle with one angle known and the length of the adjacent sides:

$$A = \frac{1}{2} \times a \times b \times \text{sine}\ \theta = \frac{1}{2} \times 70.7\ \mathrm{ft} \times 161.2\ \mathrm{ft} \times \text{sine}\ \ 59.0$$
$$= \frac{11{,}396.84'0.8571\ldots}{2} = \frac{9768.99\ldots}{2} = 4884.49\ldots \text{ or } 4880\ \mathrm{ft}^2$$

Shape E is the same as shape D. The area of shape E is:

$$A = \frac{1}{2} \times a \times b \times \text{sine}\,\theta = \frac{1}{2} \times 161.2\text{ ft} \times 150.0\text{ ft} \times \text{sine}\,38.3$$

$$= \frac{24180 \times 0.61977\ldots}{2} = \frac{14986.25\ldots}{2} = 7493.12\ldots \text{ or } 7490\text{ ft}^2$$

Now that the area for each shape is known, the total area (A_T) is calculated by combining the areas for the individual shapes:

$$A_T = A_A + A_B + A_C + A_D + A_E$$

$$= 3330\,\text{ft}^2 + 2650\,\text{ft}^2 + 2240\,\text{ft}^2 + 4880\,\text{ft}^2 + 7490\,\text{ft}^2$$

$$= 20{,}590 \text{ or } 20{,}600\,\text{ft}^2$$

The total area is 20,600 square feet.

13.11 Determining Areas of Irregular-Shaped Fields Using Trapezoidal Equations

Occasionally it becomes necessary to determine the area of a field or other property that has one irregular-shaped boundary. This is a very common problem when one of the boundaries is formed by surface water. In this situation the area is determined by dividing the shape into a series of trapezoids and summing the individual areas.

Problem What is the area (acres) for the field illustrated in Fig. 13.16?

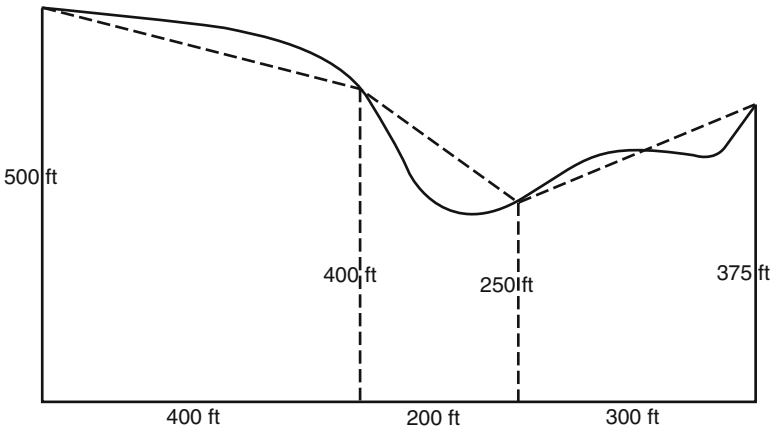

Fig. 13.16 Example of using trapezoids for irregular shape

Solution The total area (A_T) is the sum of each trapezoidal shape (dashed lines):

$$A = h \times \frac{a+b}{2}$$

$$A_T = \left(h_1 \times \frac{a_1+b_1}{2}\right) + \left(h_2 \times \frac{a_2+b_2}{2}\right) + \left(h_3 \times \frac{a_3+b_3}{2}\right)$$

$$= \left(400\,\text{ft} \times \frac{500\,\text{ft}+400\,\text{ft}}{2}\right) + \left(200\,\text{ft} \times \frac{400\,\text{ft}+250\,\text{ft}}{2}\right)$$

$$+ \left(300\,\text{ft}' \; \frac{250\,\text{ft}+375\,\text{ft}}{2}\right)$$

$$= (400 \times 450) + (200 \times 325) + (300 \times 312.5)$$

$$= 180{,}000 + 65{,}000 + 93{,}750 = 338{,}750\text{ft}^2$$

$$A(\text{ac}) = \frac{1\,ac}{43{,}560\,\text{ft}^2} \times 33{,}8750\,\text{ft}^2 = 7.776 \text{ or } 7.78\,ac$$

The total area is 7.78 acres.

The field illustrated in Fig. 13.16 contains approximately 7.78 acres. Why is it approximate? The dashed lines used to define the trapezoidal shapes only approximate the actual boundary lines of the field (Fig. 13.17).

When the irregular boundary is uniform enough to allow a series of equal distances (d) along the base line to be established, the summation trapezoidal equation can be used. Study Fig. 13.16 and the following equation for an illustration of this method:

$$A = d \times \left(\frac{h_o}{2} + \sum h + \frac{h_n}{2}\right)$$

where A = Area; d = Distance between offsets (must be equal); h_o and h_n = End offsets measured from base line AB; $\sum h$ = Summation of all interior offsets (excluding the two end offsets).

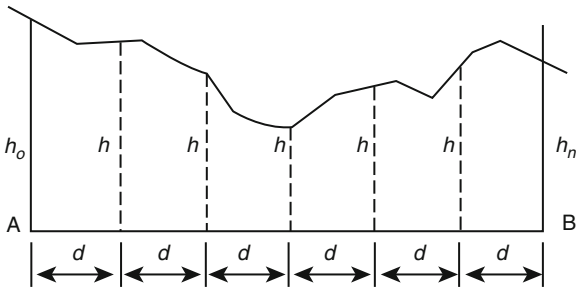

Fig. 13.17 Sketch for summation trapezoidal equation

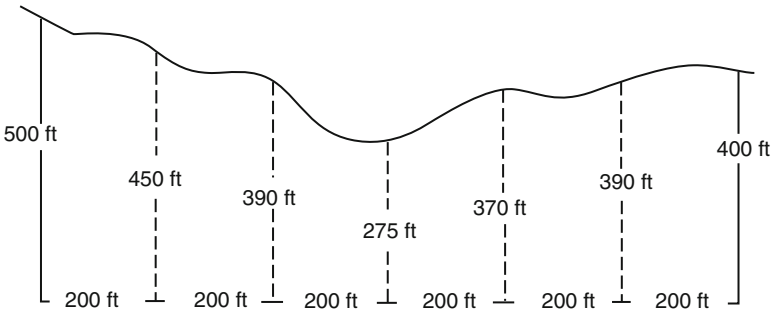

Fig. 13.18 Summation trapezoidal equation applied to a field

To use the summation equation, the field length, *AB*, is divided into a number of equal distances (d), and the offsets (perpendicular distances from line *AB* to the curved edge of the field), h, are measured and recorded.

Problem Determine the area (ac) of the irregular-shaped field illustrated in Fig. 13.18.

Solution

$$A = d \times \left(\frac{h_o}{2} + \sum h + \frac{h_n}{2}\right)$$

$$= 200\,\text{ft} \times \left(\frac{500\,\text{ft}}{2} + (450\text{ft} + 390\text{ft} + 275\text{ft} + 370\text{ft} + 390\text{ft}) + \frac{400\,\text{ft}}{2}\right)$$

$$= 200\,\text{ft} \times (250\text{ft} + 450\text{ft} + 390\text{ft} + 275\text{ft} + 370\,\text{ft} + 390\,\text{ft} + 200\,\text{ft})$$

$$= 200\,\text{ft} \times 2325\,\text{ft} = 465{,}000\,\text{ft}^2$$

$$A(ac) = \frac{1\ ac}{43{,}560\ \text{ft}^2} \times 465{,}000\,\text{ft}^2 = 10.67\ldots \text{or } 10.7\ ac$$

The field contains 10.7 acres.

13.12 Metric Problems

Problem What is the area of a triangle (ha) with a base 150.0 m long and a height of 100.0 m?

Solution

$$A = \frac{1}{2} \times 150.0\,\text{m} \times 100.0\,\text{m} = 7500\,\text{m}^2$$

$$\text{ha} = \frac{1\ \text{ha}}{10{,}000\,\text{m}^2} \times 7500\,\text{m}^2 = 0.75\,\text{ha}$$

The area is 0.75 hectares.

Problem Determine the area (m^2) for a triangle having sides measuring 650.0 m, 428.0 m, and 282.0 m.

Solution

$$S = \frac{a+b+c}{2} = \frac{650.0\,\text{m} + 428.0\,\text{m} + 282.0\,\text{m}}{2} = 680.0\,\text{m}$$

$$A = \sqrt{680.0\,(680.0-650.0)\,(680.0-428.0)\,(680.0-282.0)}$$

$$= \sqrt{680.0\,(30.0)\,(252.0)\,(398.0)}$$

$$= \sqrt{2{,}046{,}038{,}400}$$

$$= 45{,}233.15598 \text{ or } 45{,}230\ \text{m}^2$$

The area of the triangle is 45,230 square meters.

Problem Determine the area (m^2) of a triangle with sides of 350.0 m and 555.0 m and an included angle of 45°.

Solution

$$A = \frac{1}{2} \times a \times b \times \text{sine}\,\theta = \frac{1}{2} \times 350.0\,\text{m} \times 555.0\,\text{m} \times \text{sine}\,45$$

$$= \frac{194{,}250}{2} \times 0.7071 = 68{,}677.74\ldots \text{ or } 68{,}700\,\text{m}^2$$

The area of the triangle is 68,700 square meters.

Problem What is the area (m^2) of a rectangle measuring 1320.0 m by 660.0 m?

Solution

$$A = b \times h = 1320.0\,\text{m} \times 660.0\,\text{m} = 871{,}200\,\text{m}^2$$

The area of the rectangle is 871,200 square meters.

Problem What is the area (ha) of a parallelogram where the base measures 1050.0 m and the height measures 750.0 m?

Solution

$$A\,(\text{ha}) = b \times h \times \frac{1\ \text{ha}}{10{,}000\,\text{m}^2} = 1050.0\,\text{m} \times 750.0\,\text{m} \times \frac{1\,\text{ha}}{10{,}000\,\text{m}^2}$$

$$= \frac{787{,}500}{10{,}000} = 78.75 \text{ or } 78.8\,\text{ha}$$

The area of the parallelogram is 78.8 hectares.

Problem Find the area of a circle (m^2) having a radius of 75.0 m.

Solution

$$A\,(\text{m}^2) = \pi \times r^2 = 3.14\ldots \times 75.0^2 = 17{,}671.45\ldots \text{ or } 17{,}700\,\text{m}^2$$

The area of the circle is 17,700 square meters.

Problem Find the area of a sector (m^2) having a radius of 135.0 m and an angle of 60.0°.

Solution

$$A = \frac{\pi \times r^2 \times \theta}{360} = \frac{3.14 \times (135.0\text{m})^2 \times 60.0^0}{360}$$

$$= \frac{3{,}433{,}590}{360} = 9537.75 \text{ or } 9450\,\text{m}^2$$

The area of the sector is 9450 square meters.

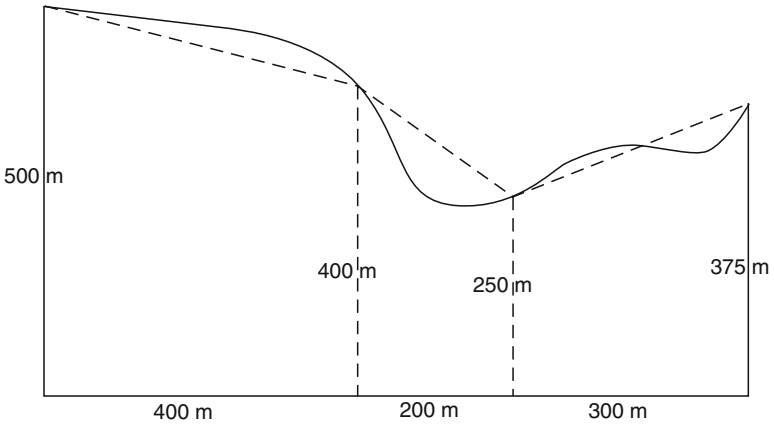

Fig. 13.19 Metric example of using trapezoids for irregular shape

Problem What is the area of a sector (ha) if the radius is 100.0 m and the arc length is 210.0 m?

Solution

$$A\,(\text{ha}) = \frac{r \times \text{arc length}}{2} \times \frac{1\ \text{ha}}{10{,}000\,\text{m}^2}$$

$$= \frac{100.0\,\text{m} \times 210.0\,\text{m}}{2} \times \frac{1\,\text{ha}}{10{,}000\,\text{m}^2} = \frac{21{,}000}{10{,}000} = 2.1\,\text{ha}$$

The area of the sector is 2.1 hectares.

Problem What is the area (ha) of a trapezoid with parallel sides of 300.0 m and 450.0 m and with a height of 120.0 m?

Solution

$$A = h \times \left(\frac{a+b}{2}\right) \times \frac{1\ \text{ha}}{10{,}000\ \text{m}^2}$$

$$= 120.0\,\text{m} \times \left(\frac{300.00\,\text{m} + 450.00\,\text{m}}{2}\right) \times \frac{1\ \text{ha}}{10{,}000\ \text{m}^2}$$

$$= 4.5\ \text{ha}$$

The area of the trapezoid is 4.5 hectares.

Problem What is the area (ha) for the field illustrated in Fig. 13.19?

Solution The total area (A_T) is the sum of each trapezoidal shape (dashed lines):

$$A = h \times \frac{a+b}{2}$$

$$A_T = \left(h_1 \times \frac{a_1 + b_1}{2}\right) + \left(h_2 \times \frac{a_2 + b_2}{2}\right) + \left(h_3 \times \frac{a_3 + b_3}{2}\right)$$

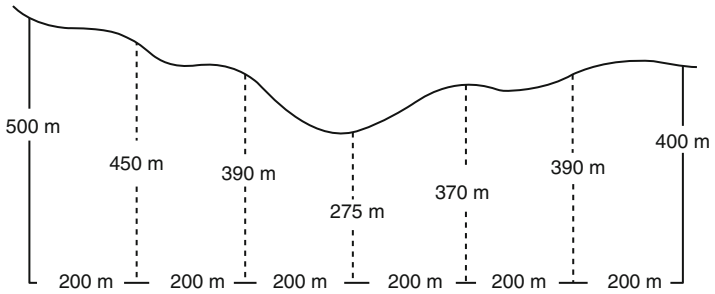

Fig. 13.20 Summation trapezoidal equation applied to a metric measured field

$$
\begin{aligned}
A\,(\mathrm{m}^2) &= \left(400\,\mathrm{m} \times \frac{500\,\mathrm{m} + 400\,\mathrm{m}}{2}\right) + \left(200\,\mathrm{m} \times \frac{400\,\mathrm{m} + 250\,\mathrm{m}}{2}\right) \\
&\quad + \left(300\,\mathrm{m} \times \frac{250\,\mathrm{m} + 375\,\mathrm{m}}{2}\right) \\
&= (400 \times 450) + (200 \times 325) + (300 \times 312.5) \\
&= 180{,}000 + 65000 + 93750 = 338{,}750\,\mathrm{m}^2 \\
A(\mathrm{ha}) &= \frac{1\,\mathrm{ha}}{10{,}000\,\mathrm{m}^2} \times 33{,}8750\,\mathrm{m}^2 = 33.875 \text{ or } 33.9\,\mathrm{ha}
\end{aligned}
$$

The area of the irregular field is 33.9 hectares.

Problem Determine the area (*ac*) of the irregular-shaped field illustrated in Fig. 13.20.

Solution Using the summation equation:

$$
\begin{aligned}
A &= d \times \left(\frac{h_\mathrm{o}}{2} + \sum h + \frac{h_\mathrm{n}}{2}\right) \\
&= 200\,\mathrm{m} \times \left(\frac{500\,\mathrm{m}}{2} + (450\,\mathrm{m} + 390\,\mathrm{m} + 275\,\mathrm{m} + 370\,\mathrm{m} + 390\,\mathrm{m})\right. \\
&\qquad \left. + \frac{400\,\mathrm{m}}{2}\right) \\
&= 200\,\mathrm{m} \times (250\,\mathrm{m} + 450\,\mathrm{m} + 390\,\mathrm{m} + 275\,\mathrm{m} + 370\,\mathrm{m} \\
&\quad + 390\mathrm{m} + 200\,\mathrm{m}) \\
&= 200\,\mathrm{m} \times 2325\,\mathrm{m} = 465{,}000\,\mathrm{m}^2 \\
A(\mathrm{ha}) &= \frac{1\,\mathrm{ha}}{10{,}000\,\mathrm{m}^2} \times 465{,}000\,\mathrm{m}^2 = 46.5\,\mathrm{ha}
\end{aligned}
$$

The area of the field is 46.5 hectares.

Chapter 14
Land Description

14.1 Objectives

1. Be able to understand the three common methods of describing land
2. Be able to use the rectangular system to read and write legal descriptions
3. Be able to use the rectangular system to determine the number of acres from a written description

14.2 Introduction

From earliest times, there was a need to mark and describe the boundaries of parcels of land. It is recorded that in about 1400 B.C., Egypt developed a system to reestablish land boundaries after each flood. The need to accurately establish and describe land boundaries has persisted to this day. To transfer ownership, one must be able to describe what land is being considered and where it is located. In the United States, a unique description for each parcel of land is required to collect property taxes. Three primary systems are used in the United States to define land boundaries and locations. These are metes and bounds, block and lot, and the Public Land Survey System (PLSS) sometimes called the rectangular systems. The metes and bounds system was used to describe the land in the original colonies and for most of the land between the Appalachian Mountains and the Mississippi river. A form of metes and bounds was also used to describe land in the Spanish and Mexican land grants. Block and lot are commonly used when land is platted for development, and the PLSS was first used to describe the Ohio River valley and later the land acquired in the Louisiana Purchase. The following sections will explain these in more detail.

14.3 Metes and Bounds

The metes and bounds system is based on a verbal or written description of a boundary using visible land marks. The description includes a point of beginning (POB), such as a rock, tree, stake, or post, and lengths and bearings of successive lines from this point.

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Lengths may be paces or in units of chains, poles, or rods. As the technology available for surveying improved, these units were replaced by feet and inches, decimal feet, or metric measurements. The bearings may be magnetic, true, or grid. True or grid bearings are the preferred type. To read or write land descriptions with the metes and bounds system, the units used and the type of bearing used must be known.

A typical description might read as follows: "beginning at the large rock about 2 min walk northly from the creek, thence easterly 100 paces to the red oak tree, thence southerly 250 paces to a large partially buried rock, thence westerly to the creek and follow the creek northly to the point of beginning." The dilemma that anyone faces trying to trace the boundaries many years later should be obvious, physical attributes change. Creeks change course, trees are removed, and rocks can be dug out or covered when land leveling.

14.4 Block and Lot

This system is very common in cities where land has been platted. City or county recorders' offices have plat books giving the location and dimensions of all the blocks and lots. In most areas, developers are required to provide such plans and have them approved before construction begins. A typical description might read: "Country Club plat, block 4, lot 23, book 543, page 201." In addition, each parcel may be identified by street number.

14.5 Rectangular System

The PLSS or rectangular system of public land survey was used in 30 states. The system was adopted in 1785 by the Continental Congress to subdivide new lands northwest of the Ohio River in a logical and systematic manner. In general, the system establishes a grid by dividing the land by a north and south line that follows a true meridian and by a base line that follows a latitude; see Fig. 14.1.

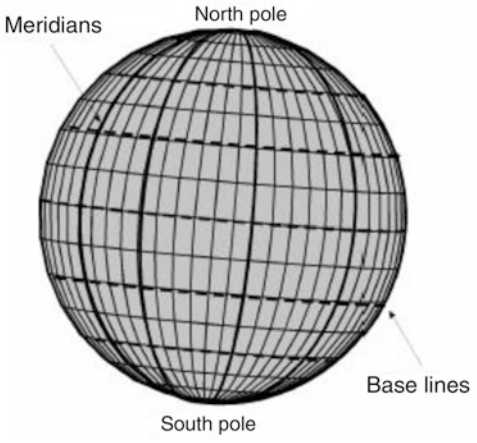

Fig. 14.1 Meridians and base lines

To establish the grid, additional lines parallel to the base line are laid out at 24 mile intervals. These are called standard parallels. To complete the grid, lines perpendicular to the base lines were also added at 24 mile intervals. These are called guide meridians. A few of the original PLSS surveys used lines 30 miles apart, but the PLSS was soon changed to a 24 mile grid. This grid is called a quadrangle and is the largest grid used in the PLSS. In this discussion, we will consider only the 24-mile grid. The quadrangles are divided into townships that are 6 miles square. The townships are further divided into 36 sections of approximately 640 acres each, and each section is still further subdivided into fractional parts (Fig. 14.2). Note: not all sections are 640 acres because of convergence.

Study Fig. 14.1 and notice that the meridian lines converge at the poles. Because the meridians converge, at the poles, it is mathematically impossible to have a true square grid. The northern boundary will be shorter than the southern boundary. The intent was to produce sections of land measuring one mile on each side. Instead of adjusting each section for convergence, any variation because of convergence was placed in the western column and the top row of sections in each township. For this reason the guide meridians, Fig. 14.2, are not continuous but have an adjustment at each standard parallel. A description of the subdivisions follows:

1. *Quadrangles*: These square like tracts are approximately 24 miles on each side.
2. *Townships*: Each quadrangle contains 16 townships, each approximately 6 miles on a side.
3. *Sections*: Each township is divided into 36 sections, each approximately one mile on a side and containing 640 acres.

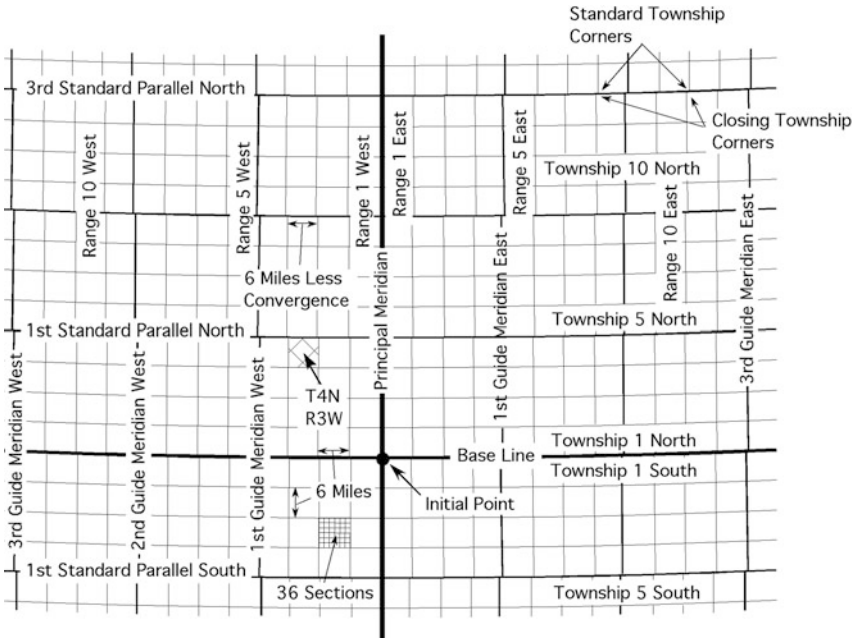

Fig. 14.2 Rectangular system of public surveying

4. *Quarter sections*: Each section is divided into quarter sections approximately one-half mile on a side and containing 160 acres. Quarter sections may be divided into fractional areas, the individual tracts containing 80, 40, 20, 10, or 5 acres or combinations of these acres.

To begin an original survey, an initial point was established in each new area of land by astronomical observations. Thirty seven initial points were eventually established. After the initial point was established, the base and the principal meridian were established through each initial point. The principal meridian may be designated by name or by number. The Oklahoma Territory was surveyed from two different meridians, the Indian Meridian and the Cimarron Meridian. The territory that became the states of Kansas, Colorado, and Nebraska was surveyed from the same meridian, but in these states, the principal meridian was identified as the 6th Prime Meridian.

In Fig. 14.2, find the initial point, base line, and principal meridian. Note that quadrangles are bounded on the north and the south by true parallels of latitude, (dark horizontal lines) called standard parallels, which are 24 miles apart and are numbered consecutively north and south of the base line. For example, the First Standard Parallel North is 24 miles north of the base line, and the Fourth Standard Parallel North is 96 miles north of the base line. The east and west boundaries of quadrangles follow true meridians, but because of the adjustment for convergence, they are not continuous; therefore, they are called guide meridians (dark vertical lines). They are 24 miles apart and numbered consecutively east and west of the principal meridian. Thus, the First Guide Meridian West is 24 miles west of the principal meridian, and the Third Guide Meridian East is 72 miles east of the principal meridian.

Because the guide meridians are true meridians, they converge as they approach the North Pole and the South Pole. This causes the north side of each quadrangle to be slightly less than 24 miles. To adjust for convergence, a closing corner is set at the intersection of each guide meridian and each standard parallel or base line. The distance between the closing corner and the standard corner causes an offset in the meridian.

Townships are bounded on the north and the south by township lines and on the east and west by range lines. Range lines are true meridians and thus converge. The south boundary of each township is 6 miles in length, but the north boundary is slightly less. Closing corners are established for townships in the same way that they are established for quadrangles. Township lines are parallel to the base line and the standard parallel.

A township is identified by a unique description based upon the principal meridian governing it. A north–south column of townships is called a range. Ranges are numbered in consecutive order east and west of the principal meridian. An east–west row of townships is called a tier. Tiers are numbered in order north and south of the base line. By common practice, the word "tier" usually is replaced by "township" or just "T" in designating the rows.

An individual township is identified by its number and direction north or south of the base line, followed by the number and direction east or west of the principal meridian. The township designation usually is abbreviated, as for example, "T5 N, R3E" of the prime meridian. This township would be located between 24 and

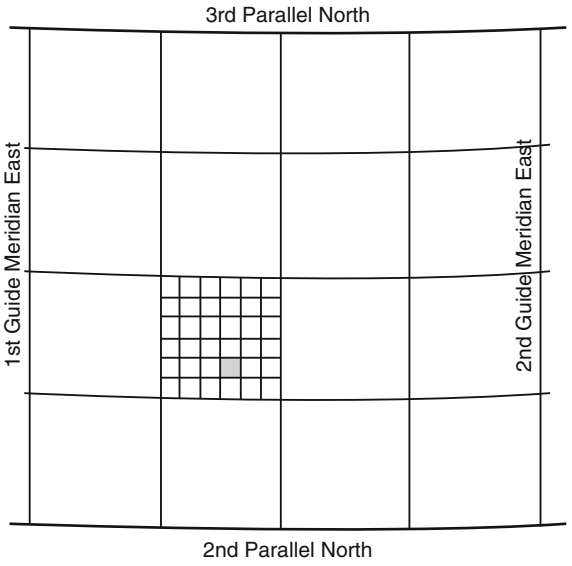

Fig. 14.3 Division of quadrangle and township

30 miles north and 12 and 18 miles east of the initial point. Figure 14.3 shows a quadrangle divided into townships and one township divided into sections.

Based on earlier discussion, the township divided into sections in Fig. 14.3 would be identified as T10 N, R6E.

Figure 14.4 shows the method of subdividing a township into 36 sections, nominally one mile square (640 acres). Sections are numbered by starting in the northeast corner of the township and continuing in a serpentine fashion. If the survey is error free, which is extremely improbable, all sections are one mile square except those along the west and north boundary of the township. These sections are less than one mile in width because of convergence of the range lines and any error in measurements. If the highlighted section in Fig. 14.4 is part of the township in Fig. 14.3, the description would read S21, T10 N, R6W, Principal Meridian (or PM).

Fig. 14.4 Section numbers in township

6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36

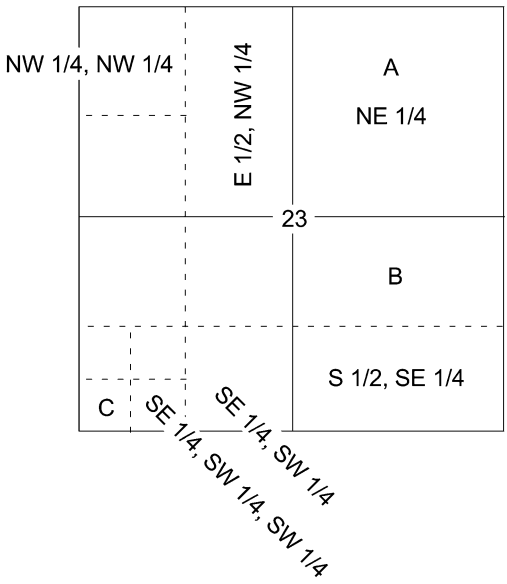

Fig. 14.5 Subdivision of a section

As shown in Fig. 14.5, each section may be further subdivided into smaller tracts, with north being to the top of the page and east to the right.

The fractions refer to the fraction of the section subdivision being considered and only 1/4 and 1/2 are used unless using lot numbers. The rectangular description of the section subdivisions begins with the smallest unit of area.

Problem What are the descriptions of the subdivisions labeled A, B, and C in Fig. 14.5? Assume the same township as Fig. 14.3.

Solution

A = NE 1/4, S23, T10 N, R6E, PM.
B = N 1/2, SE 1/4, S23, T10 N, R6E, PM.
C = SW 1/4, SW 1/4, SW 1/4, S23, T10 N, R6E, PM.

The description for subdivision A is read as: "the northeast one quarter of section 23, located in township 10 north and range 6 east of the Principal Meridian."

It is not unusual for a field to be contained in more than one fraction of a section. In these situations, a "&" can be used to link the parts.

Problem What is the description of the field in Fig. 14.6?

Solution When faced with an illustration like Fig. 14.6, draw the fractional lines before attempting to write the descriptions (Fig. 14.7).

With the fractional lines drawn, it is easier to see that the answer is NE1/4, SE1/4, NW1/4 & SW1/4, NE1/4.

Land descriptions also can be used to determine the acres contained in each subdivision. To determine the acres, divide the area of a section, 640 acres, by each of the denominators in the fractions.

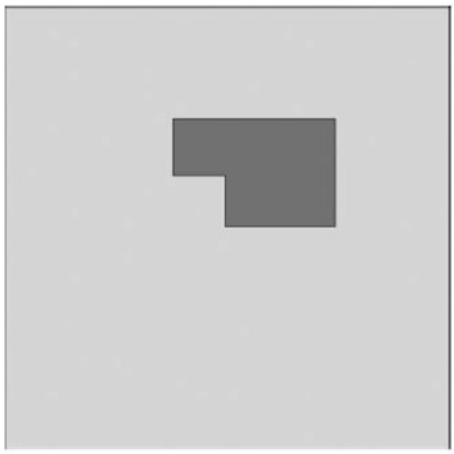

Fig. 14.6 Fractions of a section using "&"

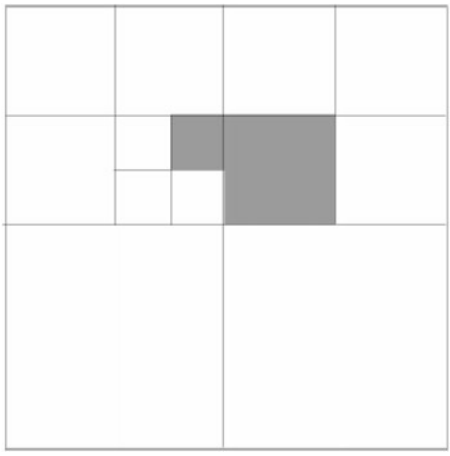

Fig. 14.7 Solution of fractions of section using an &

Problem What is the area (acres) for each of the subdivisions labeled A, B, and C in Fig. 14.5?

Solution Because a section is nominally 640 acres, the areas are:

$$\text{A} : 640 \times \frac{1}{4} = 160\,\text{acres}$$

$$\text{B} : 640 \times \frac{1}{2} \times \frac{1}{4} = 80\,\text{acres}$$

$$\text{C} : 640 \times \frac{1}{4} \times \frac{1}{4} \times \frac{1}{4} = 10\,\text{acres}$$

14.6 Metric Problems

The PLSS is unique to the United States, and there is no comparable system in the SI units.

Chapter 15
Differential and Profile Leveling

15.1 Objectives

1. Be able to describe the equipment used in differential and profile surveying
2. Be able to understand the terms used in differential and profile leveling
3. Be able to read a surveying rod
4. Be able to identify and control the common sources of error during leveling
5. Be able to describe the processes of differential and profile leveling
6. Be able to record a set of notes for differential and profile leveling

15.2 Introduction

Leveling is the process of determining the elevation of points on, above, or below the surface of the earth and the angles and the distances between them. Different types of surveys can be used depending on the desired results. Differential and profile leveling are two surveying methods that are very useful for agricultural and horticultural projects. They are both useful for planning and layout of projects. For planning purposes, they are used to provide the site information needed to develop the maps, charts, and drawings necessary for building structures, roads, drains, etc.

Differential and profile leveling can also be used for layout. When used to layout a structure, road, drain, etc., the dimensions and other information from a plan are transferred to the ground. Differential and profile leveling rank next to the measurement of distance in importance as a surveying technique. This chapter will discuss the terms, equipment, and procedures for differential and profile leveling.

15.3 Leveling Terms

15.3.1 Benchmark

A benchmark (BM) is an object whose elevation above mean sea level is known or assumed to be known. A benchmark must be an object that is dimensionally stable because it is a reference point. If the benchmark elevation is accidentally changed,

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all surveys that used it as a reference must be redone. Using benchmarks allows surveys to be repeated. If a common benchmark is used, a surveyor can tie information from the one survey to the information collected in a different survey. A network of benchmarks can thus be established over a large area, all tied to the same reference elevation. Benchmarks may vary in character and permanency according to the survey for which they were established. The US Geological Survey (USGS) established a nationwide network of benchmarks, all referenced to mean sea level. These benchmarks consist of bronze disks set in concrete monuments which have been firmly set in the ground. These bronze disks will include information such as the agency that established the benchmark, the date of the survey, the elevation, and/or benchmark number. The adoption of Global Positioning Satellites (GPS) for surveying has provided another means of establishing benchmarks.

In many situations, it is not necessary to know the exact elevation above sea level. For such surveys, a local or temporary benchmark is used. Frequently, this benchmark is given the elevation of 100.00 feet. If the terrain is hilly, the surveyor should choose a number larger than 100.00 feet for the starting elevation. This is to ensure no negative numbers for elevations.

When using a local benchmark, the survey crew must select and establish its location. Two rules should be followed. The object selected should (1) be reasonably permanent for as long as it will be needed, and not easily moved or otherwise destroyed, and (2) be capable of being described in such a way that it can be easily located. A typical local benchmark might be an "X" chipped in a concrete curb or a bridge abutment, an iron pin driven firmly into the ground, or the rim of an electrical or sewer access. It is the job of the note keeper to describe accurately the name, number, type, elevation, and location of each benchmark. This information is recorded on the right-hand page of the traditional surveying notebook.

15.3.2 Backsight

A backsight (BS) is a rod reading taken on a point of known or assumed elevation. Two common stations for backsights are benchmarks and turning points. A backsight is the vertical distance between the line of sight through the instrument and the point the rod is set on. When a Philadelphia or similar type rod is used, the vertical measurement will be in units of decimal feet.

The backsight reading is used to establish height of the instrument; see Fig. 15.1. A backsight will always be taken on a benchmark or a turning point.

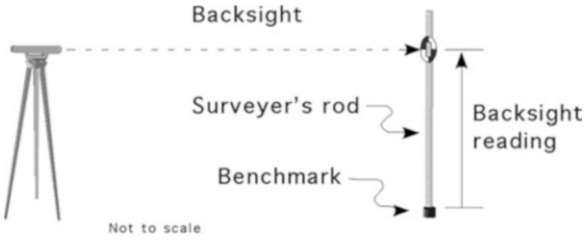

Fig. 15.1 Backsight rod reading

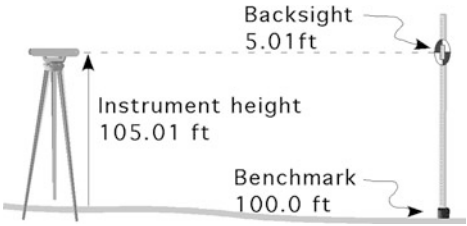

Fig. 15.2 Determining instrument height

A backsight on a turning point is used to continue a survey beyond the starting instrument position. The word "backsight" has nothing to do with the direction in which the instrument is pointed. It is important to remember that there is usually only one backsight for each setup of the instrument.

15.3.3 Height of Instrument

The height of instrument (HI), also called instrument height (IH), is the elevation of the line of sight through the instrument when it is mounted on a tripod and leveled.

It is found by adding the backsight rod reading to the elevation of the point on which the backsight was taken. In Fig. 15.2, the benchmark elevation is 100.0 feet, and the rod reading is 5.1 feet. The instrument height is 105.1 feet because the line of sight through the instrument is 5.01 feet higher than the benchmark.

15.3.4 Foresight

A foresight (FS) is a rod reading taken on any point of unknown elevation. The purpose of the foresight is to determine the elevation for the site. In differential leveling, there is only one foresight for each instrument setup, whereas profile leveling may have several foresights per instrument setup.

The FS is subtracted from the HI to find the elevation of the unknown point. In Fig. 15.3, the foresight rod reading, 3.21 feet, is subtracted from the instrument height, 105.01 feet, to determine the elevation at the unknown point, 101.8 feet.

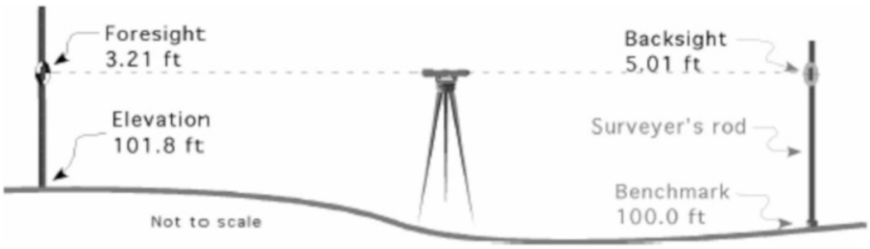

Fig. 15.3 Foresight rod reading

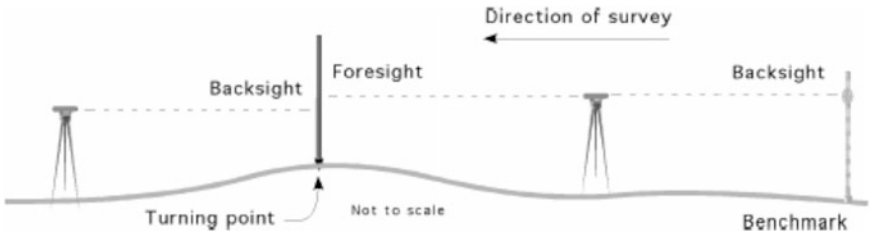

Fig. 15.4 Turning point

15.3.5 Turning Point

A turning point (TP) is a temporary benchmark that is established to extend a survey a greater distance than one instrument setup. Whenever the instrument is moved to a different location, a backsight is taken on a TP if the benchmark is not available. In differential surveys, turning points are usually used wherever the starting station and ending station cannot be seen from one instrument position. In profile surveys TPs are used whenever the view of a foresight is obstructed.

The number of turning points used during a survey depends on the data being collected and the topography. Two additional factors that influence the number is the maximum distance for the instrument and the distance traveled; see Fig. 15.4. They should be selected with care and must not be moved until the survey is complete. The structure used for a turning point should be dimensionally stable just like a benchmark. Do not set the rod on the ground when making a turning point; doing so could result in a serious error.

15.4 Surveying Equipment

The equipment used in leveling consists of a leveling instrument and a leveling rod. The most common type of level is called an engineer's or a dumpy level. The leveling instrument is a telescope containing both vertical and horizontal cross hairs and one or more spirit levels (bubble in a liquid-filled tube) to indicate when the instrument base is horizontal. The entire assembly, consisting of the frame, telescope, and spirit level, can be "leveled" by turning the three or four leveling screws that hold the frame in position above the tripod head.

Another common level is the hand level. It usually has a spirit level for holding it horizontal and one set of cross hairs. More sophisticated models may also have stadia hairs and direct-reading angle scales.

The traditional leveling rod is a wooden scale about 1 inch by 2 inches in cross section and about 14 feet long, graduated in feet, tenths, and hundredths of feet. Rods measuring in feet and inches and meters and centimeters are also available. Rods are used to measure the vertical distance between the line of sight through the telescope and the object on which the leveling rod is resting.

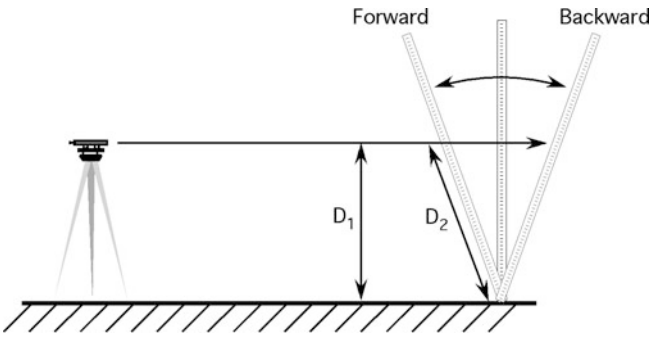

Fig. 15.5 Rocking the rod

15.5 Rocking a Rod

A rod is used to measure the vertical distance between the line of sight established by the instrument and the object on which the rod is resting. To provide an accurate reading, it must be held in a vertical position. Failure to hold the rod in a vertical position is a common error in surveying. The easiest way to ensure that the rod is vertical is to use a rod level. If a rod level is not available, the instrument person (person on the instrument) can determine if the rod is vertical to the left or the right by instructing the rod person to move the rod until it is aligned with the vertical cross hair of the instrument. The fore and aft alignment with the instrument must be controlled by the rod person. When a rod level is not available, the fore and aft vertical position of the rod can be determined by rocking the rod. When rocking the rod, the rod person slowly rocks the rod forward and backward past vertical while maintaining the left and right alignment. The instrument person records the shortest reading. This is illustrated in Fig. 15.5.

The shortest reading will occur when the rod is vertical. The distance D_1 will always be less than distance D_2.

15.6 Reading a Philadelphia Rod

The most common type of rod is known as the Philadelphia type. This rod has two sections, each approximately 7 feet long that can be extended to give continuous readings from zero at the base to 13.00 feet at the top. The graduations consist of black marks painted on a white background. The black graduations are 0.01 feet thick and are spaced 0.01 feet apart. The size of the graduations allows the rod to be read to the nearest 0.01 feet, directly for distances up to 250 feet. The tenths of a foot are indicated by black numerals, and each foot is indicated by a larger red numeral. The foot interval usually is also indicated by a small red numeral between the whole foot marks. Figure 15.6 is read as 7.02 feet.

When the sight distance is greater than 250 feet, or if the rod cannot be read directly for any reason, the target should be used. The target, Fig. 15.7, is a round or oval disk divided into quadrants, which are alternately red and white. When the rod

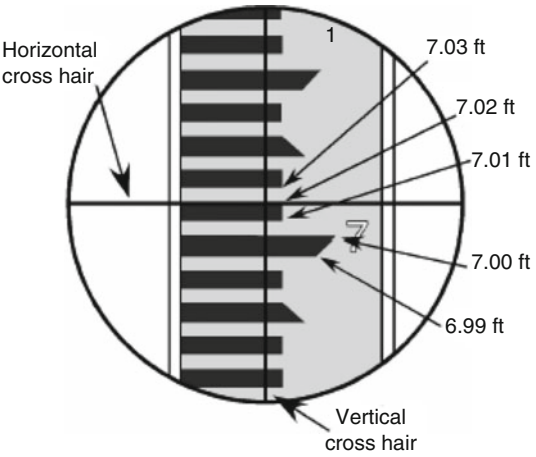

Fig. 15.6 Reading a Philadelphia rod

cannot be read directly, the instrument person can signal the rod person to raise and lower the target until it is aligned with the horizontal cross hair of the instrument. The notetaker can then record the reading when the rod holder calls it out. The target also has a vernier scale that allows readings to be made to 0.001 ft. The reading for the rod in Fig. 15.7 is 5.753 ft. When using the vernier scale on the target, the notetaker stays with the rod person.

15.7 Setting Up a Surveying Level

Many different types and variations of levels are used for surveying. The following procedure for setting up an engineer's level will also work with most other types. When not in use, the instrument is housed in a case for protection. To be used, it must be removed from this case and carefully threaded on the tripod head. The tripod legs are set about 4 feet apart and pushed firmly into the ground, thereby

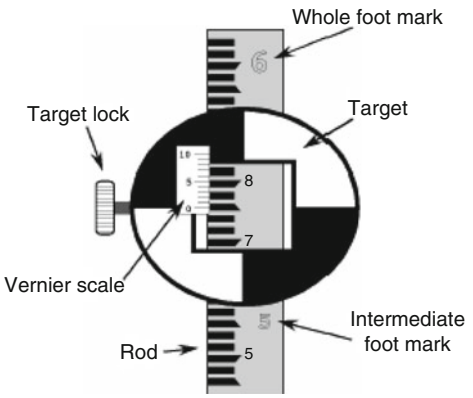

Fig. 15.7 Reading the rod using a target

providing a stable base for the instrument, which is necessary for an accurate survey. If the tripod is set up with the head nearly horizontal, leveling of the instrument will be much easier and faster.

To level a four-legged (four leveling screws) instrument, the telescope is lined up over one pair of leveling screws, and the bubble is centered. This is accomplished by turning the screws under the instrument spirit level in opposite directions. The leveling process is expedited when the left thumb rule is used; the bubble in the level moves in the direction of the left thumb. Then the telescope is lined up over the other pair of leveling screws and centered again by turning the two screws under the spirit level following the left thumb rule. The procedure is repeated until the bubble remains centered for any position of the telescope. The leveling screws should not be over tightened, or they will bind and put excessive strain on the instrument frame or left loose; the instrument will rock and not remain level.

To level a three-legged instrument, the telescope is aligned over any one of the three leveling screws. The instrument is leveled with the adjusting screws and the spirit level. Once leveled, the telescope should be slowly rotated to check the accuracy of the leveling.

15.8 Common Sources of Error

The accuracy of leveling can be greatly improved if several common errors are controlled:

1. *Instrument out of adjustment*: Anytime that the instrument is "bumped" or otherwise moved, it must be re-leveled. It is a good practice to check the leveling bubble both before and after reading the rod. Note: resetting the level may change the instrument height. It must be checked, and if different, all or some of the measurements will need to be repeated.
2. *Rod not plumb*: The rod must always be held plumb using a rod level or rocked back and forth as explained in the section on rocking the rod. A good method of plumbing the rod is to stand behind the rod and balance it carefully on the stake by holding your hands lightly on each side.
3. *Parallax*: If the cross hairs appear to move over the rod as the eye is shifted slightly to the side or up and down, parallax exists. When parallax exists, the line of sight of the eye may not be parallel to the line of sight of the instrument. This source of error is eliminated by adjusting the eyepiece until the cross hairs are the darkest. Because the eyepiece will need to be adjusted for each person, standard practice is for just one person taking all the readings.
4. *Sights not equal*: When field conditions permit, the distance of backsights and foresights from the instrument should be as nearly equal as possible. Errors due to the instruments being out of level are minimized because they tend to cancel out. This is more true for differential surveys than other types.
5. *Reading the rod incorrectly*: The person reading the rod must be very careful to ensure that the correct foot mark is used and that the target is used correctly.

15.9 Recording Field Notes

Engineers and surveyors have developed a standard practice for recording surveying information because it is important that the notes be clear, complete, and easy to read. Professional surveyors use electronic instruments whenever possible. These instruments record the data and download it to a data collector or computer for post-processing and/or use. When electronic instruments are used, the format of the data is determined by the software driving the instrument. The software may provide options for the format of the data.

For small projects and when mechanical equipment is used, the traditional field book is still used. The field book is divided into right-hand and left-hand pages. The left-hand page contains the title, the location, and the data. The right-hand page of the notes is used to record information about the weather, survey party, and equipment and describe the location of the benchmarks, turning points, creeks, fence or property lines, or any information that is important for the use of the data. The location of the benchmark, or starting point, is also described in the notes. A sketch of the general area, showing the location of the beginning and ending stations of the survey, benchmarks, ditches, roads, and other landmarks, also is helpful (Fig. 15.8).

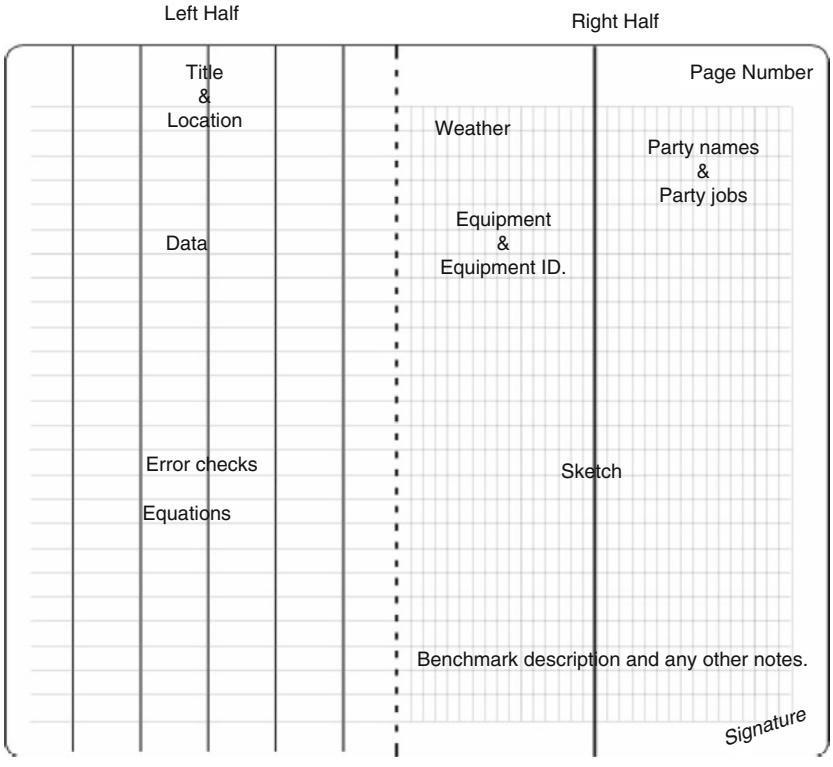

Fig. 15.8 Standard form for field notes

Good surveying practices dictate that the data be checked for errors if at all possible. In differential leveling, the accuracy is checked by "closing the loop." Closing the loop, or just closure, means surveying or measuring back to the beginning point. When completing a differential leveling activity, surveying from BM2 to BM1 should find the same difference in elevation as the first leg of the survey from BM1 to BM2. This is rarely the case however because some errors are always present in leveling. The amount by which the original BM1 elevation and the BM1 elevation calculated from loop closing fail to agree is called the error of closure. The closing of the survey is conducted following the same procedure as the first leg of the survey. The instrument is picked up, moved, leveled, and a backsight is taken on BM2. The survey is completed using the necessary foresights and backsights to survey back to BM1.

15.10 Differential Leveling

Differential leveling is the process of finding the difference in elevation between two or more points. When the two points are within the sight limits of the instrument, two readings are taken. The difference in rod readings represents the difference in elevation between the two points. When one or more of the points are beyond the range of the instrument, turning points are required.

One of the most common applications of differential leveling is to run a circuit of sights to determine the elevations of one or more benchmarks relative to a previously established benchmark. The procedure for differential leveling will be described using this type of circuit, illustrated schematically in Fig. 15.9. The diagram shows that three instrument setups were made in traveling from BM1 to BM2. Also note that a "return check" was made between BM2 and BM1 and that three more setups were made in this phase of the survey.

The survey begins with the instrument person going forward a convenient distance (not exceeding the limits of the instrument) and setting up the level, following the procedure previously described. The instrument person sights on the rod, while it is held on the top of BM1 by the rod person and notes a center cross hair reading of 3.03 feet. This is the backsight; therefore, the 3.03 feet rod reading is added to the BM1 elevation (assumed 100.00 feet), resulting in a height of instrument (HI) of 103.03 feet. The rod person then moves forward past the instrument and selects a turning point, TP1. The FS rod reading of this TP1 is 3.86 feet. The foresight is subtracted from the HI, and the elevation of TP1 is found to be 99.17 feet. The instrument can now be moved forward and set up at a new position beyond the turning point. A backsight rod reading of 2.60 feet is observed on TP1 and added to the TP1 elevation of 99.17 feet, giving an instrument height of 101.77 feet. The end of the survey has not been reached so a new turning point, TP2, is established and an FS rod reading of 4.53 feet is recorded. This rod reading is

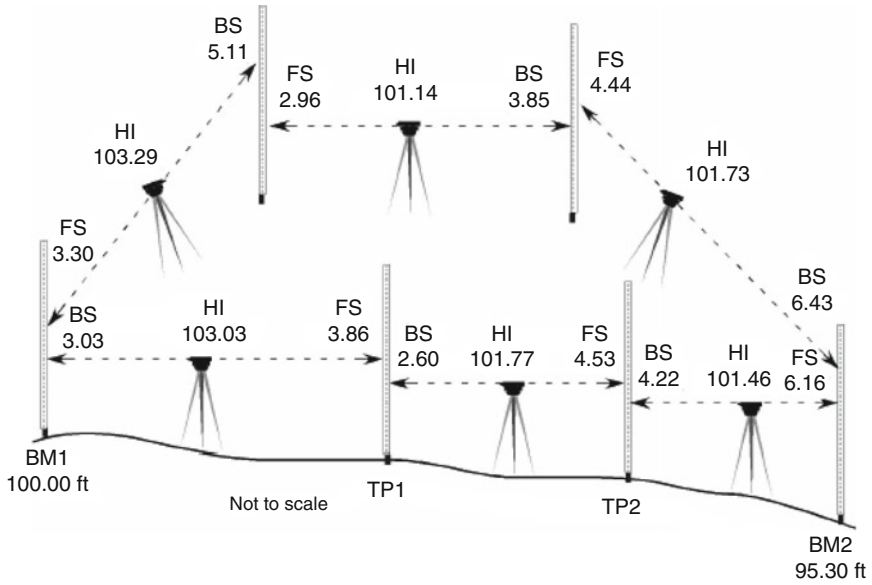

Fig. 15.9 Differential leveling

subtracted from the HI of 101.77 feet, giving the elevation of 97.24 feet for TP2. This process is repeated a third time and the elevation of BM2 is found to be 95.30 feet. We now know that the difference in elevation between BM1 and BM2 is 100.00 feet minus 95.30 feet, or 4.7 feet, assuming no errors were made.

In summary, the procedure for differential leveling is as follows:

1. Set up the instrument.
2. Take the BS reading on BM1.
3. Establish the TP, if needed, and take the FS reading.
4. Move the instrument and set up again.
5. Take the BS on the TP.
6. Establish the next TP and take the FS reading.
7. Move the instrument and set up again.
8. Repeat steps 5–7 until a foresight is taken on the last station.

The data for the differential leveling survey in Fig. 15.9 are recorded in the data table (Table 15.1). The left-hand page of a standard surveying field notebook contains five columns. These columns are needed for the column headings of station (STA), backsight (BS), height of instrument (HI), foresight (FS), and elevation (ELEV). Additional columns may be added as needed to record additional information, for example, the distance for each sight.

Table 15.1 Data for differential leveling example

STA	BS	HI	FS	ELEV
BM1	3.03			100.00
		103.03		
TP1	2.60		3.86	99.17
		101.77		
TP2	4.22		4.53	97.24
		101.46		
BM2	6.43		6.16	95.30
		101.73		
TP3	3.85		4.44	97.29
		101.14		
TP4	5.11		2.96	98.18
		103.29		
BM1			3.30	99.99

15.10.1 Error Control

In surveying, it is important to control as many errors as possible. For differential leveling surveys, three error checks should be completed: close the loop, note check, and calculation of the allowable error of closure. The survey is closed to provide the information for the other two checks. The note check is conducted to catch any mathematical errors in the notes. The rule for checking notes states that the absolute value of the sum of the foresights minus the sum of the backsights must be equal the absolute value of the difference (Δ) in elevation for BM1 (beginning and closure elevation). Expressed mathematically:

$$|\Sigma \text{FS} - \Sigma \text{BS}| = |\Delta \,\text{Elevation}\,\text{BMI}|$$

Problem Are the field notes in Table 15.1 accurate?

Solution

ΣBS	ΣFS
3.86	3.03
4.53	2.60
6.16	4.22
4.44	6.43
2.96	3.85
3.30	5.11
25.25	25.24

$$|\Sigma \text{FS} - \Sigma \text{BS}| = |\Delta \,\text{Elevation}\,\text{BMI}|$$
$$|25.25 - 25.24| = |100.00 - 99.99|$$
$$0.01 = 0.01.$$

The note check equation is true, this means the 0.01 feet difference in the elevation of BM1 is not caused by a math error in the data table. An error that is discovered after the fact cannot be corrected; therefore, the next step is to determine if the error is acceptable.

The third check is determining the allowable error of closure. The allowable error of closure procedure was established because surveyors realized that it was impossible to survey without some error. When perfection is not possible, limits of acceptability must be established. The equation for allowable error of closure sets the acceptability limits for surveys.

$$\mathrm{AE} = K\sqrt{M}$$

where AE is the allowable error; K is a constant ranging from 0.01 to 1.0; M is the distance traveled (mi).

The value used for K is determined by the level of accuracy needed for the survey. A high-order survey, one with very little allowable error, would use a K value of 0.01. A very low-order survey, one where more error is acceptable., might use a K value of 1.0. The order of survey must be established before the survey is started because it will determine the quality of the equipment and the procedures that must be followed to collect the data. A K value of 0.10 or 0.05 is acceptable for most general construction and agricultural surveys.

Problem Is the closure error of 0.01 ft. for the differential leveling survey in Fig. 15.9 acceptable if the total distanced surveyed, out and back, was 3600 ft. and a K value of 0.10 is acceptable?

Solution

$$\mathrm{AE} = K\sqrt{M} \;=\; 0.10 \times \sqrt{3600\,\mathrm{ft} \times \frac{1\,\mathrm{mi}}{5280\,\mathrm{ft}}} = \; 0.10 \times \sqrt{0.6818\ldots} = \; 0.08.$$

The closure error is acceptable, $0.01 < 0.08$.

15.11 Profile Leveling

Profile leveling is used to establish changes in elevation along a line. Common lines requiring profile surveying are drains, roads, fences, and retaining walls. When the results of a profile survey are plotted as a graph, the line will enable one to establish grades, find high or low spots, and make estimates of depths of cuts and many other decisions. The following sections will illustrate the procedure for profile leveling and the preferred way to record the data.

Before a profile can be made, the surveying crew establishes the stations by setting a stake or flag where the rod readings are to be taken. When the terrain is uniform, the stakes can be set as fixed distance apart (25, 50, or 100 feet). When the terrain is not uniform or when there are addition stations that need to be recorded such as a sidewalk, the survey crew reconnoiters the line and establishes a station at

each important point. Because the purpose of the profile is to show the true slope of the ground, the irregularity of the terrain will largely determine where the stations should be established. When there is a definite change in the slope of the ground, the crew should set a stake to determine the elevation, even if it does not fall at a uniform distance.

The major difference between profile and differential surveying is the addition of additional foresights that are used to define the profile of the route. These additional foresights are called intermediate foresights, and they are treated differently during the error checks on the notes. Table 15.2 shows that a common way to record the intermediate foresights is to identify the true foresights with parenthesis. An additional method is to add a column to the table for the intermediate foresights.

Once the centerline of route is established, the distance from the starting point to each station is accurately measured. For higher level surveys, 2 × 2 inch stakes may be driven flush with the ground surface and rod readings taken on the tops of the stakes. On less important surveys, the foresights may be taken with the rod set directly on the ground. Next, the level is set up, readings are taken for each station, and elevations are established for each station. Turning points are used as needed to complete the survey. Finally, a closing circuit of readings must be made to check the accuracy of the survey. This is accomplished by completing a differential survey back to the starting benchmark. Figure 15.10 illustrates the steps for conducting a profile leveling survey. The data for this survey is in Table 15.2.

Table 15.2 Data for profile leveling

STA	BS		HI		FS	ELEV
BM1	6.02		106.02			100.00
0.00					7.34	98.68
100					5.76	100.26
225					3.67	102.35
290	1.72		107.40		(0.34)	105.68
340					4.03	103.37
400					6.65	100.75
460	4.00		107.28		(4.12)	103.28
TP2	3.34		105.27		(5.35)	101.93
BM1					(5.25)	100.02
ΣBS	15.08	ΣFS		15.06		
|ΣFS − ΣBS| = 0.02						
|ΔElevation| = 100.02–100.00 = 0.02						
0.02 = 0.02 Notes check						
Acceptable error = 0.10 {EQ\r(920 ÷ 5280)} = 0.04						
0.02 < 0.04 Closure error acceptable						

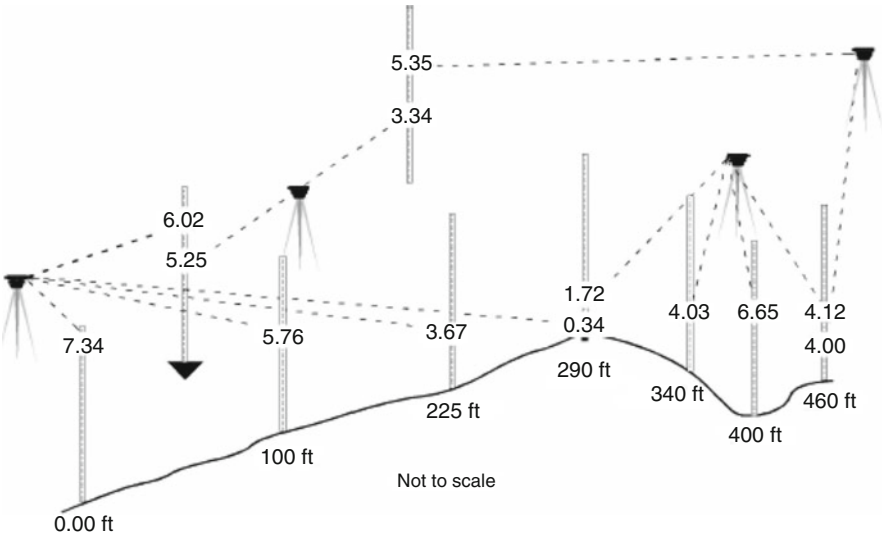

Fig. 15.10 Profile example

With the level set up near the line to be profiled, the rod is held on the benchmark, and a reading of 6.02 feet is recorded. This establishes the height of the instrument as 106.02 feet (100.00 + 6.02). Next, the rod is held at stations 000, 100, 225, and 290, where rod readings of 7.34, 5.76, 3.67, and 0.34 feet are recorded. It is evident that station 290 feet is also a turning point. At station 290, a stake is set flush with the surface. The elevation of each point is calculated by subtracting the rod reading from the height of instrument. Notice that the same HI is used for all stations up to and including 290, as all readings are made from the same instrument setup.

Because the surveying crew anticipated in advance the need for a turning point, the profile leveling exercise is continued by moving the instrument to a new location to provide a view of the remaining stations. A backsight of 1.72 feet is observed on station 290 establishing the new height of instrument as 107.40 feet. The survey continues by recording the rod readings for stations 340, 400, and 460. These readings are 4.03, 6.65, and 4.12 feet.

The profile leveling survey is completed by closing the circuit. The instrument is moved, and a backsight of 4.00 feet is observed on station 460. A stake is set at TP2, and a foresight of 5.35 feet is observed. The procedure is repeated to complete the survey from TP2 to BM1.

Table 15.2 contains a set of notes for this survey. Note the similarities and differences between these notes and Table 15.1 (data for differential leveling). At the completion of the survey, the closing error was 0.02 feet.

15.11.1 Error Control

Because profile leveling notes usually have more foresights than backsights, the method of checking for math errors is slightly different from the method used for differential leveling. The difference is the exclusion of the intermediated foresights in the note check. The only foresights to be included when calculating the sum of the foresights (ΣFS) are those taken on turning points and benchmarks, including stations if they were used as TPs. In the sample notes, Table 15.2, the foresight readings that are to be used for checking are shown in parentheses. The data in Table 15.2 indicate that there were no arithmetic errors in the survey, and the closure error was acceptable. *Note*: this procedure provides a check on the turning points only—not the intermediate foresights. Any errors in the rod readings for the intermediate foresights will not be detected using the standard checks for error. Additional methods such as multiple reading or plunging the telescope must be used. Extreme care must be used to prevent mistakes in reading and recording the rod readings and in calculating the elevations at all stations.

15.12 Using Profile Data

The results of profile leveling surveys are most useful when they are plotted. The principal purposes for plotting a profile are (1) to aid in the selection of the most economical grade, location, and depth of irrigation canals, drainage ditches, drain tile lines, sewer lines, roads, etc., and (2) to determine the amount of cut or fill required for these installations. The graph is plotted with the elevation on the ordinate (vertical scale) and the stations on the abscissa (horizontal scale).

The use of computer spreadsheets makes it much easier to plot and complete "What if?" examples using surveying data.

Problem What will be the maximum depth of cut for the data in Table 15.2 to install a drain at 2.0 ft. below the elevation of station 0.0 with a slope of 0.5%?

Solution This problem could be answered by calculating the difference in elevation between each station and the proposed drain but that would require a calculation for almost every station. Plotting the data will provide the visual information to determine where the greatest depth will be (Fig. 15.11).

The plot shows that the maximum elevation of the profile is 105.7 feet. At that station, the elevation of the drain will be at 98.20 feet.

$$105.7\,\text{ft} - 98.20\,\text{ft} = 7.5\,\text{ft}.$$

The maximum depth of cut to install the drain is 7.5 feet.

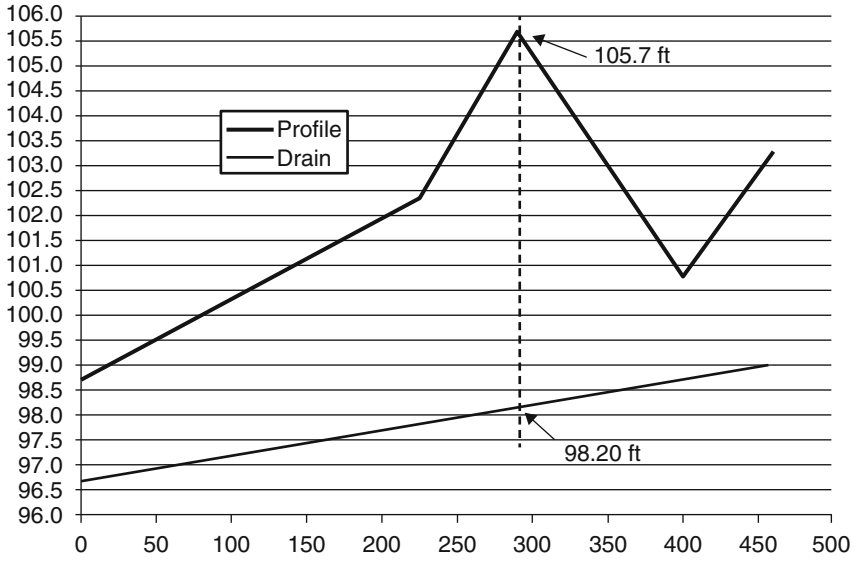

Fig. 15.11 Profile plot of example data with drain

The problem could also be solved by calculating the difference in elevation between the profile and the drain for each station surveyed using the equation:

$$\text{Elevation}_{\text{drain}} = \text{Elevation}_{\text{starting}} + (\text{Station distance} \times \text{Slope}).$$

With a slope for the drain of 0.5%, for station 290 in the sample data, the elevation of the drain is:

$$\begin{aligned}\text{Elevation}_{\text{drain}} &= \text{Elevation}_{\text{starting}} + (\text{Station distance} \times \text{Slope}) \\ &= 96.7\,\text{ft} + (290\,\text{ft} \times 0.005) \\ &= 96.7\,\text{ft} + 1.45\,\text{ft} \\ &= 98.15 \text{ or } 98.2\,\text{ft}.\end{aligned}$$

The elevation of the profile at station 290 (105.7 feet) minus the elevation of the drain at station 290 (98.2 feet) leaves a depth of cut of 105.7–98.2 or 7.5 feet.

15.13 Metric Problems

The procedures and techniques for completing differential and profile surveys using metric equipment are the same. The only difference is that a metric rod would be used and the allowable error of closure equation is modified for metric

use. A common error of closure equation for metric differential and profile surveys is:

$$\mathrm{AE} = K\sqrt{M}$$

where AE = allowable error of closure; K = constant, 3–6 mm; M = distance surveyed, km.

Chapter 16
Weather

16.1 Objectives

1. Be able to understand the differences between high-pressure and low-pressure areas and their effect on the weather
2. Be able to identify the five common air masses
3. Be able to understand the hydrologic cycle
4. Be able to define rainfall intensity, duration, and recurrence interval
5. Be able to determine rainfall intensity when given the duration and return interval

16.2 Introduction

The weather is the largest uncontrollable variable, as well as the most unpredictable variable, in the production of agricultural products. Agricultural production is based on the growth of plants, and those plants require an optimum environment for maximum production. However, maximum production is seldom realized in the natural environment because the weather seldom matches the needs of plants. Whenever the plant environment is significantly different from the optimum, they are stressed and production is reduced. The major limiting factor is water. An understanding of weather mechanisms will improve the decision-making process for activities such as cutting hay, irrigating, harvesting, and tillage. Better decisions mean increased productivity for any agricultural enterprise. This chapter will discuss the pressure systems that influence the weather, the hydrologic cycle, and a few of the characteristics of rainfall and runoff.

16.3 Areas of High and Low Pressure

Weather at any location is greatly influenced by atmospheric pressure systems. Meteorologists track two systems, high-pressure and low-pressure. Areas of high and low pressure are predictors of weather. Winds blow in a counterclockwise direction around low-pressure centers and in a clockwise direction around

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https://doi.org/10.1007/978-3-319-69679-9_16

high-pressure centers. Closely spaced high- and low-pressure systems indicate a steep pressure gradient, and high wind speeds are possible for the area between the two pressure centers. When a high- and low-pressure system is separated by a large distance, the wind speeds will be lower. A trough line may develop between two low-pressure areas, and a ridgeline may develop between two high-pressure areas. In general, cloudy or rainy weather is associated with a low-pressure center, and clear, sunny weather accompanies areas of high pressure.

16.4 Air Masses

Differences in pressure are caused by air masses moving across the country. An air mass is a large body of air that has a more or less uniform temperature and moisture content throughout the mass. Air masses that have been over water for a period of time may contain large amounts of moisture, whereas those originating over land areas are usually drier.

The weather in the United States is influenced by five air masses, Fig. 16.1. The following section lists and briefly describes these air masses.

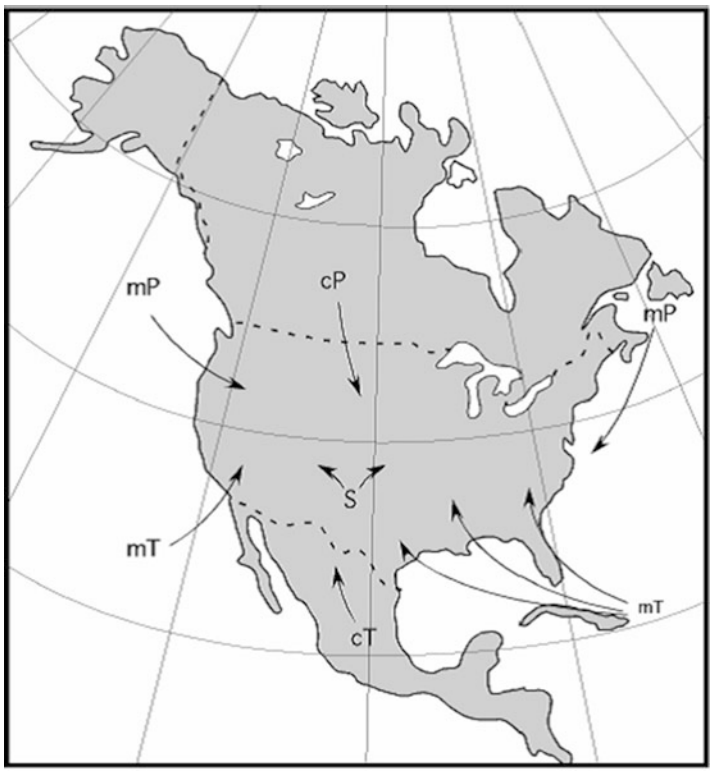

Fig. 16.1 North American air masses

1. *Tropical maritime* (mT): This air mass forms off the Gulf of Mexico where it is subject to tremendous heating by the sun. This heating causes evaporation from the ocean, resulting in a warm, moist air mass. This mass generally moves north and west into the central region of the country. This mass contributes the largest amount of moisture to the central and eastern regions of the United States. Tropical maritime air masses also form seasonally of the southern coast of California.
2. *Tropical continental* (cT): The tropical continental forms over the Mexican countryside. The cT is subject to tremendous heating by the sun; but because it forms over land, it is dry. It tends to move north into the central plains. When a cT moves into a region dominated by a mT, a dry line can develop at the boundary line between the two air masses. This condition is famous for the development of severe thunderstorms.
3. *Polar maritime* (mP): This air mass forms over the polar regions of the Pacific and Atlantic Oceans. They are very cool and usually saturated. Consequently any additional cooling can produce precipitation. They are notorious for producing fog, drizzle, cloudy weather and long lasting, light to moderate rain. The Pacific mP occurs more frequently and tends to move south and east into the central plains. As it is forced up over the Rocky Mountains, it loses most of its moisture and takes on the characteristics of a continual air mass. The Atlantic mP occurs less frequently and tends to follow the east coast.
4. *Polar continental* (cP): This mass forms over the central plains of Canada. This area of Canada has long winter nights and a large amount of radiative cooling resulting in a very cold, dry air mass. This air mass also tends to move very slowly and usually is very cold. Consequently this air mass does not produce very much precipitation. The exception is along the boundary line between the cP and a mT. In this situation the rapid cooling of the mT caused by the cP can produce localized intense thunderstorms. Its normal movement is south into the Great Plains.
5. *Superior* (S): The superior air mass is unique because it forms at high altitudes over the southwestern desert and occasionally descends to the surface. It is usually very hot and dry.

16.5 Storms

Storms are the result of conflict between warm air masses and cold air masses. The zone of contact between the contrasting air masses is called a front. Fronts are classified as cold fronts or warm fronts depending on which air mass is dominant. When the cold air mass is dominant, the change occurs quickly because cold air masses usually move rapidly. Cold air is heavier than warm air; therefore the warm air is forced upward, as shown in the cross section in Fig. 16.2.

As it rises, warm air cools rapidly. Extreme turbulence and heavy rainfall may occur over small areas. From a soil and water conservation standpoint, cold fronts may cause local rainstorms of high intensity that may result in serious soil erosion and local flooding.

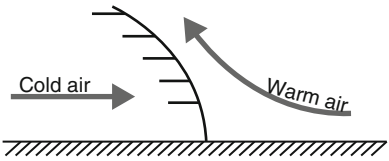

Fig. 16.2 Cross section of a cold front

A cross-sectional view of a warm front is shown in Fig. 16.3.

A warm front occurs when the warm air mass is dominant and overtakes cooler air. The rate of cooling is much less than for a cold front, and resulting rains are gentler. The rains usually cover very large areas. Thus the potential for erosion is reduced, but the rains may cause widespread flooding if they persist for a long period of time.

16.6 Hydrologic Cycle

Climatological concerns involve more than the effects of pressure and air masses on the weather. The conservation of soil and water is based on an understanding of the hydrologic cycle. Figure 16.4 illustrates the movement of water in, on, and above the earth.

The earth is a closed system in which all of the water circulates from one form to another in a cycle. A study of the cycle can begin at any point, but we will start with precipitation.

Precipitation is caused by the condensation of water vapor in the atmosphere. Water vapor collects in the atmosphere as the sun evaporates water from the oceans, rivers, lakes, and plants. It falls to the earth in the form of rain, hail, or snow or forms on the surfaces of objects as dew or frost. Not all precipitation reaches the earth's surface; some evaporates as it falls; some reaches the surface but does not move through the cycle because it is held in the form of snow and ice; and some is intercepted by plants. The moisture stored as snow and ice may be stored for a long period of time in glaciers and the polar ice caps. Precipitation follows different paths before it eventually returns to the atmosphere in the form of vapor.

A portion of the precipitation will infiltrate the soil. It is not unusual for the infiltration rate (inches/hour) of the soil to be less than the rainfall intensity (inches/hour). When this occurs, the excessive precipitation becomes runoff, which is one of the two causes of erosion. Not all runoff reaches the ocean; some evaporates, some is collected in different size impoundments and then infiltrates into the soil,

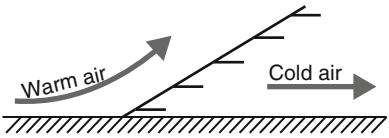

Fig. 16.3 Cross section of a warm front

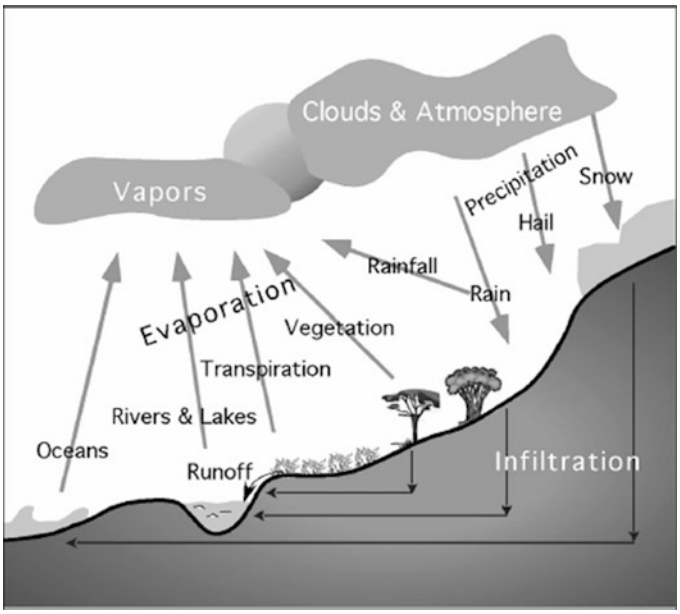

Fig. 16.4 Hydrologic cycle

and some is used by vegetation. The water used by vegetation may be evaporated quickly or may become part of the plant processes. Water can be tied up in plants for extended periods, but it eventually returns to the cycle.

The precipitation that infiltrates into the soil also takes different paths. Some may fall on areas of deep soil and percolate deeply into the earth. Other infiltration may reach an impervious layer close to the surface and start to move horizontally. The underground horizontal movement may end at some type of surface water or may flow out of the ground as a spring or an artesian well. The water that infiltrates deeper into the soil collects in aquifers. Many are small and localized, but some may form large underground basins such the Ogallala aquifer. Water in aquifers may be pumped out of the ground for domestic, industrial, or agricultural use, or it eventually may reach the ocean. Horizontal movement through the soil may be as little as a few inches per year. Once the water reaches the ocean, the sun causes it to evaporate, and the cycle begins again.

The hydrologic cycle can be used to explain the importance of water conservation. Any activities such as pumping and dam building change the amount and direction of the flow of water. For example, any water captured by a dam not only reduces the amount of water available to downstream users, but it also changes the amount of water that infiltrates into the soil and evaporates into the atmosphere. Any contamination such as chemicals or silt added to the water at one point in the cycle may remain in the water and cause problems for the next user.

16.7 Rainfall Intensity, Duration, and Recurrence

Engineers, conservationists, ecologists, and agricultural producers are interested in rainfall because of its impact on erosion, floods, and water available for crops. There are four important characteristics of rainfall: intensity, duration, total amount, and recurrence interval (for storms). These are all discussed in the following sections.

16.7.1 Intensity

Rainfall intensity is the rate of rainfall. It is usually expressed in units of inches per hour or millimeters per hour. The intensity is an important characteristic of rainfall because, other things being equal, more erosion is caused by one rainstorm of high intensity than by several storms of low intensity. A high-intensity storm will have a greater volume of runoff than a low-intensity storm.

16.7.2 Duration

Duration is the period of time that rain falls at a constant rate or intensity. It does not mean the total time, from beginning to end, of a rainfall event. During any rainfall event (storm), the rainfall intensity will not be constant. It may vary from quite high to very low; so it is necessary to think in terms of how long a specific rainfall intensity lasts (min or hr) at a certain rate (in/min or mL/min). The example of the rainfall intensity–duration for a rainfall event in Fig. 16.5 has eight (8) different durations during a rainfall event that lasted for 94 min. The total amount of rain

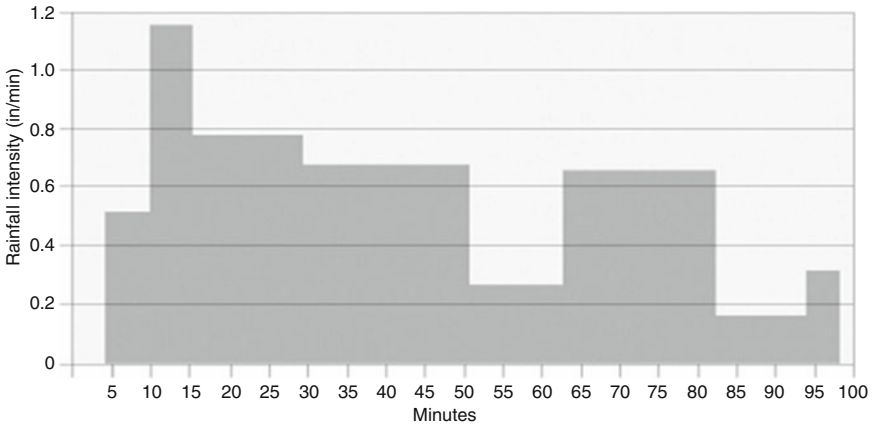

Fig. 16.5 Example of intensity–duration for a rainfall event

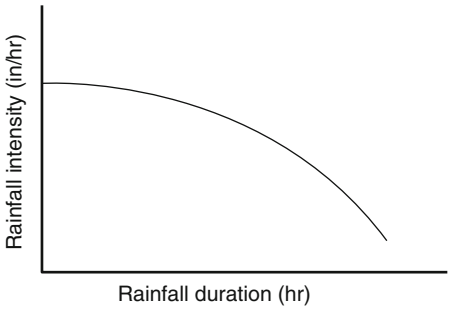

Fig. 16.6 Typical rainfall intensity–duration curve

(inches or millimeters) for a rainfall event is the sum of each rainfall intensity times the duration of that intensity.

The average rainfall intensity for a storm is between the highest and the lowest rainfall intensity. As a general rule, the high-intensity portion of a storm has a shorter duration than the low-intensity portions. A typical relationship between rainfall intensity and duration is illustrated in Fig. 16.6.

16.7.3 Recurrence Interval

Another important aspect of rain is how often a storm of a specified intensity and duration may be expected to occur. The recurrence interval is defined as the number of years (on the average) before a storm of a given intensity and duration can be expected to recur. A storm that would be expected on an average of once in 25 years is said to have a 25-year recurrence interval or is called a 25-year storm. It is important to remember that this is all based on the laws of probability or chance and that these estimates are based on averages only. There is nothing to prevent a 25-year storm from happening in two successive years, or even more than twice in 1 year, although the probability of that occurring is low.

The National Weather Service has studied the rainfall records of major storms for many years. The results of these studies have been published in the form of Rainfall Intensity Recurrence Interval Charts. Such a chart would look like Fig. 16.7.

Thus, a storm is considered to have a recurrence interval of 2, 5, 10, 25, 50, or 100 years or longer, depending on the average number of years expected to pass before a storm of similar intensity and duration occurs again. For a given duration, we would expect the intensity of a 100-year recurrence interval storm to be greater than that of a 10-year storm. A curve can be plotted showing the relationship between rainfall intensity and the expected duration for each recurrence interval.

16.7.4 Intensity–Duration–Recurrence Interval

Figure 16.8 shows typical intensity–duration–recurrence interval curves for a specific location. The lines in the chart represent the recurrence intervals of 2, 5, 10, 25, 50, and 100 years.

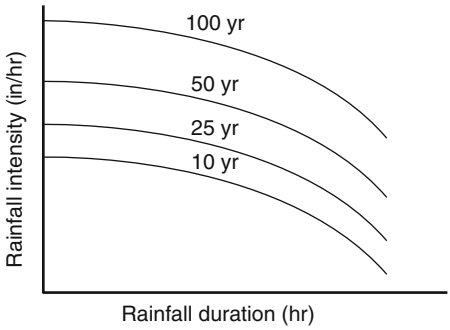

Fig. 16.7 Typical rainfall intensity–duration–recurrence interval curves

Note that both axes in the graph are logarithmic scales and must be carefully read. The time in the left half of the graph is in minutes. The time in the right half of the graph is in hours. To design water conservation structures, a graph appropriate for the area under study should be used.

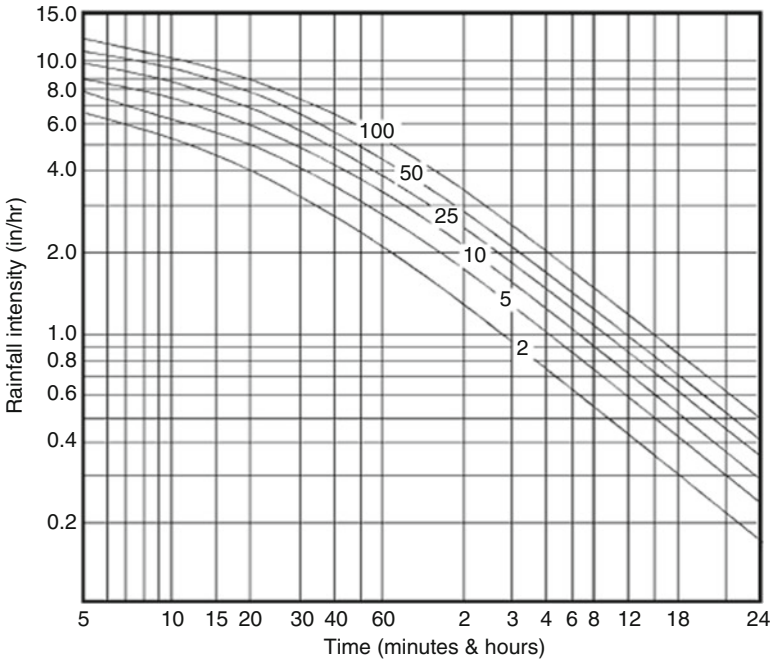

Fig. 16.8 Example of rainfall intensity–duration–recurrence interval

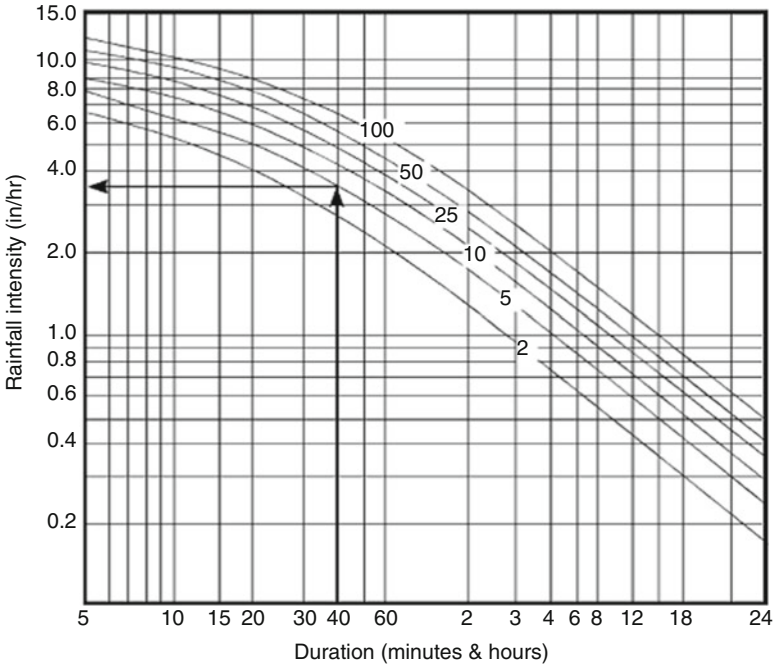

Fig. 16.9 Rainfall intensity for sample problem

Problem What is the expected rainfall intensity for a storm with a duration of 40 min and a 5-year recurrence interval.

Solution Enter the table at 40 min along the horizontal axis. Move vertically until intersecting with the 5-year curve. Move horizontally to the left until intersecting with the rainfall intensity axis. Read the rainfall intensity = 3.5 in/hr, Fig. 16.9.

16.8 Metric Problems

The hydraulic cycle is the same regardless of the units being used. The only difference is in the units used to measure rainfall. The rainfall–intensity–duration graph included in this section with SI units looks different because it is not a logarithmic graph, Fig. 16.10.

Problem Determine the rainfall intensity for a 5-year storm and duration of 20 min using SI units.

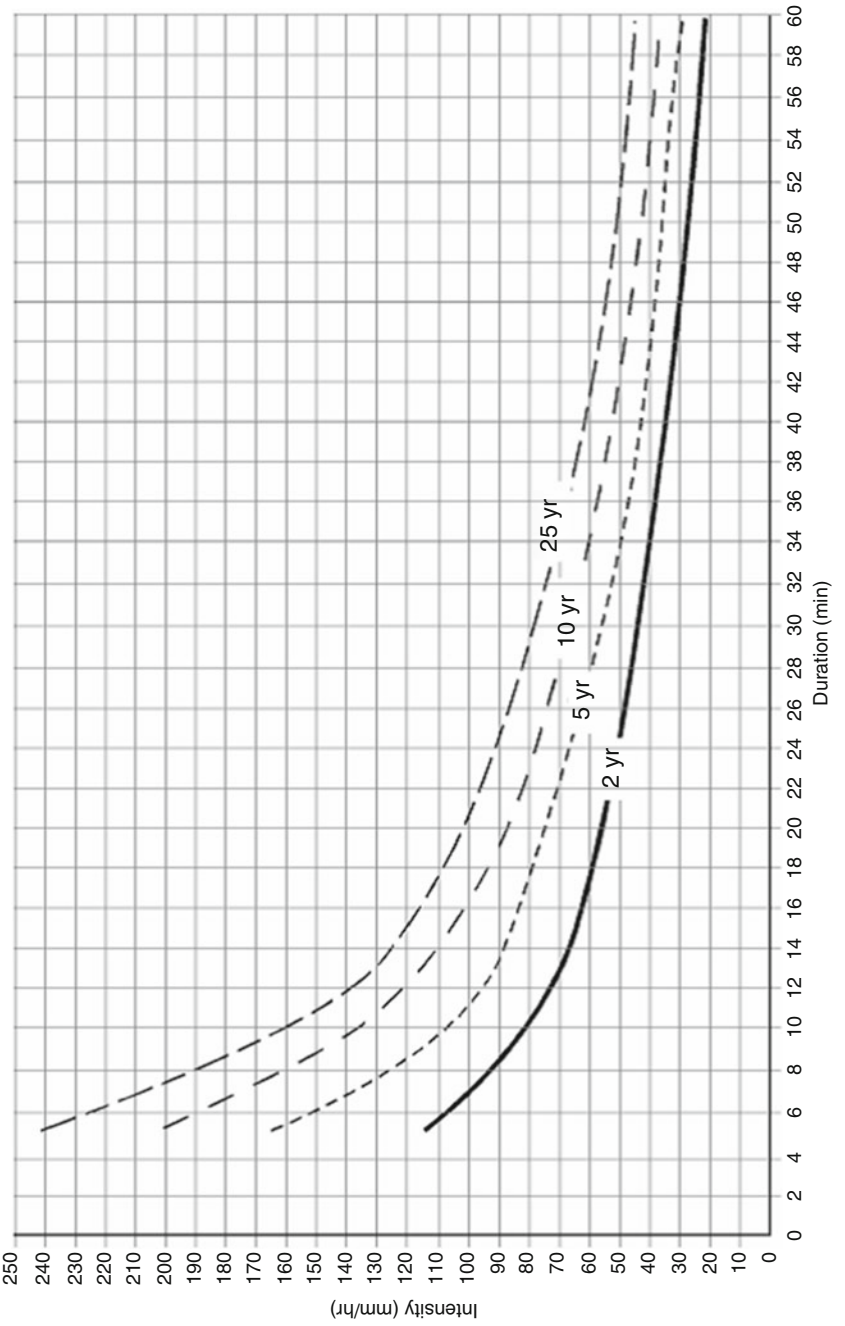

Fig. 16.10 Rainfall intensity–duration–reoccurrence interval graph with SI units

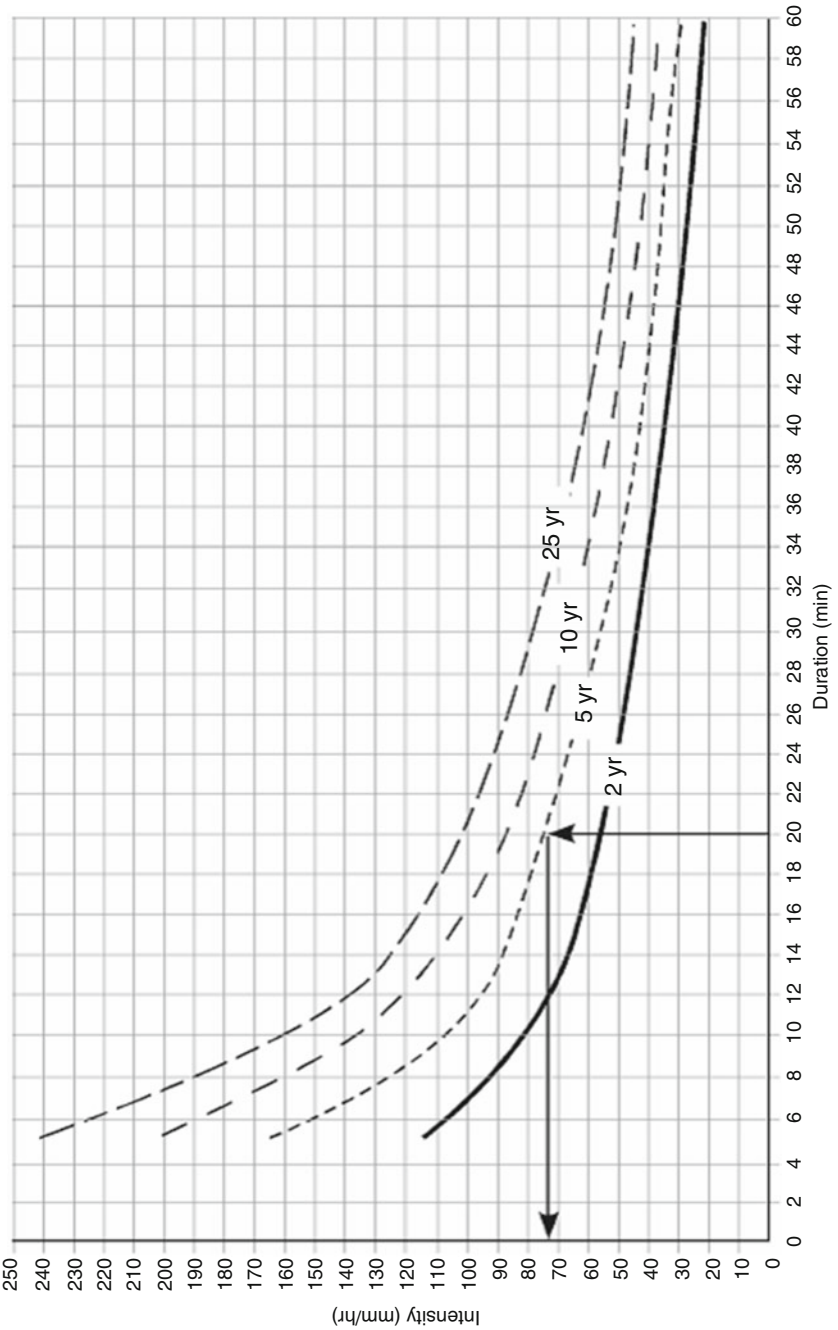

Fig. 16.11 Rainfall intensity for sample problem

Solution Enter Fig. 16.11 along the horizontal axis at the 20 min mark and move vertically to the 5-year storm curve and then move horizontally left to the rainfall intensity scale. Read rainfall intensity = 72 mm/hr.

Problem What is the expected recurrence interval for a storm with a duration of 28 min and an intensity of 70 mm/min?

Solution Move upward from 28 min duration and to the right from 70 mm/hr, Fig. 16.12. At the point where they converge, read 10-year interval.

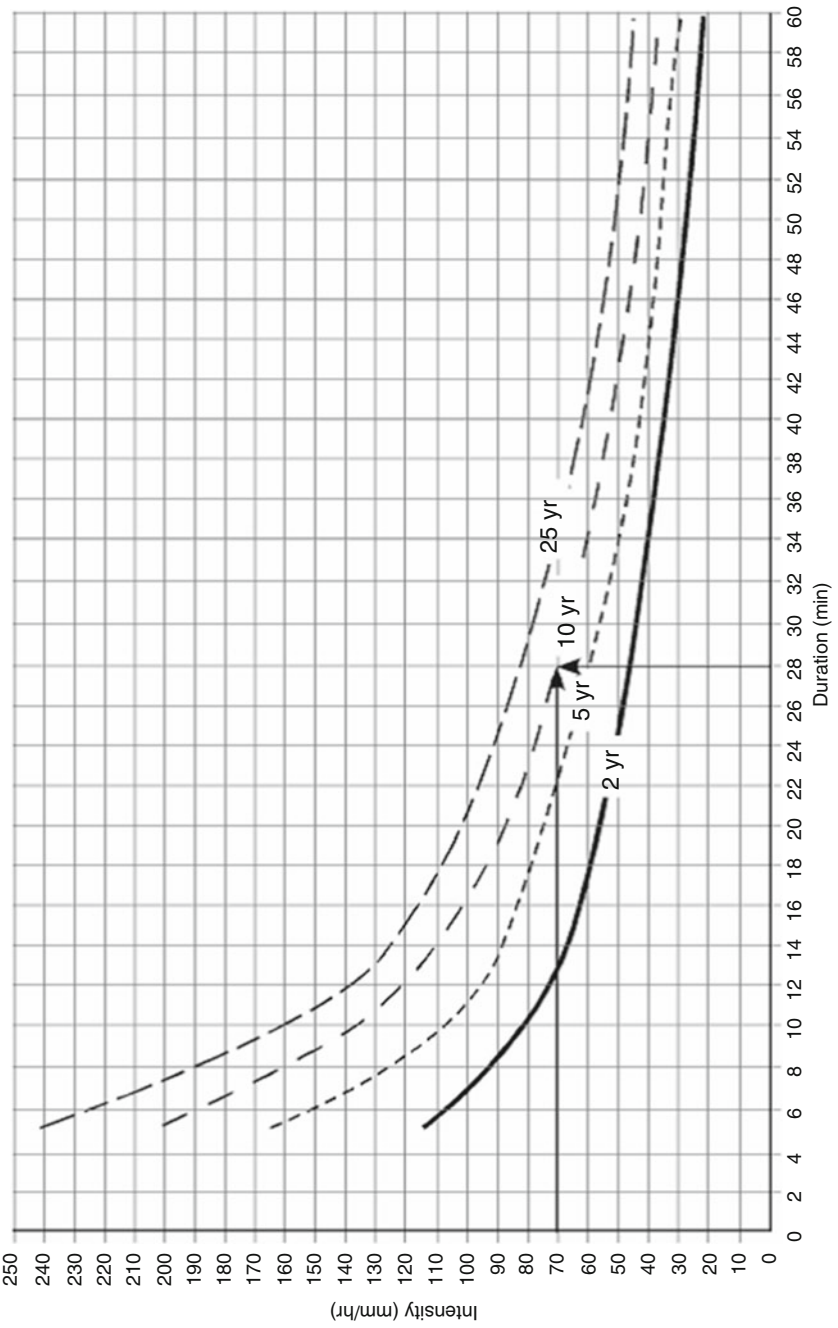

Fig. 16.12 Reoccurrence interval for sample problem

Chapter 17
Water Runoff

17.1 Objectives

1. Be able to discuss the watershed characteristics that influence water runoff.
2. Be able to use the rational method for determining peak runoff rates.
3. Be able to utilize a rainfall intensity–duration–reoccurrence interval graph.
4. Given the characteristics of a mixed watershed, be able to determine the peak runoff rate for a specified storm.

17.2 Introduction

In the previous chapter, it was determined that runoff occurs whenever the rainfall intensity exceeds the infiltration rate. Therefore to manage runoff, it is useful to know the volume of water that will run off an area and/or the maximum rate of runoff. The volume of runoff is used to size drainage structures and water impoundments. One of the uses of the peak rate is to size drainage ways, culverts, and bridges. The peak rate can be easily visualized if the flow rate is plotted in the form of a hydrograph. A hydrograph plots the runoff rate for a watershed versus time. A watershed is a drainage basin where all of the water that runs off passes through a single outlet point, Fig. 17.1.

This point may be the outlet into another stream or an impoundment like a pond or lake.

Figure 17.2 is a typical hydrograph, and it shows that runoff gradually increases to a peak rate and then drops off after the rainfall stops and the watershed drains.

Flow rates in streams are generally measured in units of cubic feet per second (cfs) or cubic meters per second (cms). This chapter will discuss the rational method, which is one method that is used to calculate the peak rate of runoff for areas less than 20 acres.

17.3 Peak Rate of Runoff

The rate of runoff is not constant for any rainfall event. Depending on the characteristics of the watershed, there will be some delay from the start of the rain until runoff starts to occur. Once runoff occurs each watershed will have a different time

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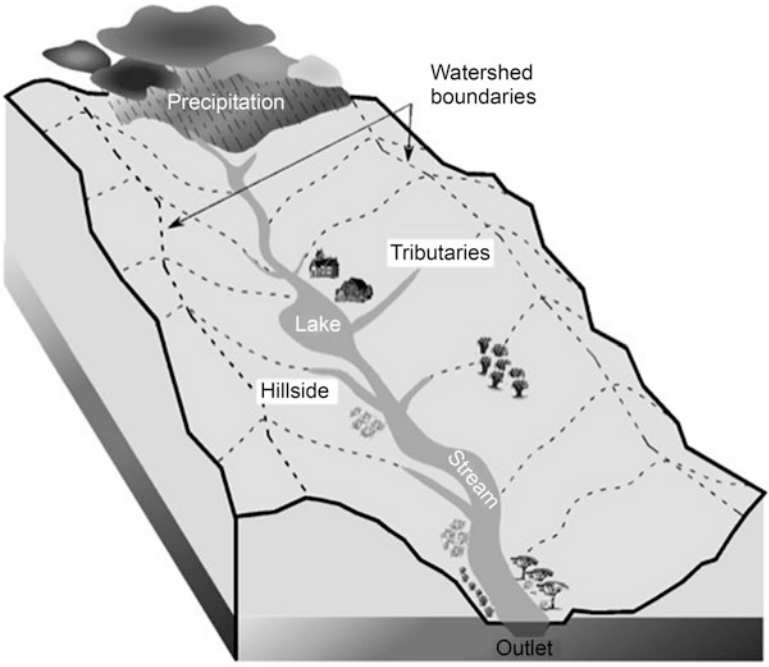

Fig. 17.1 Model of watershed

lapse from the start of the rainfall until the peak rate occurs. The effect of these differences can be seen by evaluating the hydrograph for each watershed.

The shape of the curve will be different for each rainfall event and for each watershed. For example, if the rainfall event has a longer duration, the hydrograph could look more like Fig. 17.3.

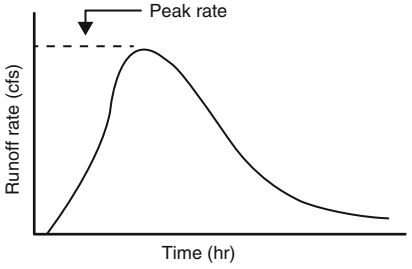

Fig. 17.2 Typical runoff hydrograph

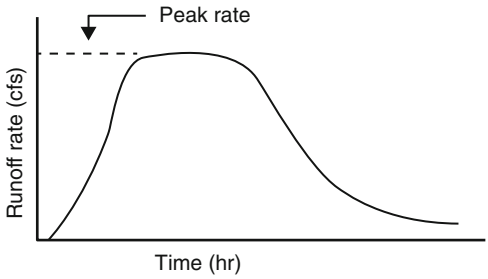

Fig. 17.3 Typical hydrograph with longer duration

17.4 Rational Method of Calculating Peak Rate of Runoff

The rational method is one of the oldest methods of calculating the peak rate of runoff, and although it is considered simplistic, it is still useful for small watersheds. It is also useful for learning the factors that affect runoff. The confidence in the output decreases as the watershed size and variability increases. For small areas that are relatively uniform, the rational method will produce acceptable results for most needs. Note: The rational method has been written for computers. The computer version includes more variables. The rational method equation is:

$$Q = CIA$$

where Q = peak rate of runoff, ft^3/sec; C = runoff coefficient; I = rainfall intensity, in/hr; A = drainage area, ac.

The accuracy of this equation as a predictor of the peak runoff rate is only as good as the accuracy of the numbers used for each of the variables. The following tables contain generalized values and should be used only as examples. When the calculations are critical, the actual values for a particular watershed should be obtained from the National Resource Conservation Service or the appropriate Web site.

17.4.1 Runoff Coefficient (C)

The runoff coefficient (C) is defined as the ratio of the peak runoff rate to the rainfall intensity. The runoff coefficient mathematically indicates for a watershed whether the runoff is likely to be high or low. The value of C depends on the type and characteristics of the watershed. Watersheds containing very tight soil, steep slopes, or cultivated land will have a high runoff rate. Watersheds containing sandy soils with flat slopes covered with good vegetation will have low runoff.

The runoff coefficient for watersheds with various topographic, soil, and cover conditions can be estimated by using the values given in Table 17.1.

17.4.2 Rainfall Intensity (I)

The rainfall intensity used in the rational method is based on a specific rainfall duration and recurrence interval. The recurrence used depends on the importance of

Table 17.1 Table of runoff coefficients (*C*)

Topography, vegetation, and slope	Soil texture		
	Sandy loam	Clay and silt loam	Tight clay
Woodland			
Flat 0–5%	0.10	0.30	0.40
Rolling 5–10%	0.25	0.35	0.50
Hilly 10–30%	0.30	0.50	0.60
Pasture			
Flat 0–5%	0.10	0.30	0.40
Rolling 5–10%	0.16	0.36	0.55
Hilly 10–30%	0.22	0.42	0.60
Cultivated			
Flat 0–5%	0.30	0.50	0.60
Rolling 5–10%	0.40	0.60	0.70
Hilly 10–30%	0.52	0.72	0.82

the project. Terraces and waterways are designed for a 10-year recurrence, whereas spillways for dams may require a design based on a recurrence interval of 100 years or more. The duration of rainfall used in the rational method is determined by the time of concentration of the watershed.

17.4.2.1 Time of Concentration

The time of concentration for a watershed is defined as the time required for water to flow from the most remote point of the watershed to the outlet. The peak rate will occur when the entire watershed contributes to the runoff.

The peak runoff flow is influenced by many factors. For the purposes of this text, the only factors that will be considered are slope and length of the drainage way. Obviously, if the drainage way is short and steep, the water will arrive at the outlet quickly and the time of concentration will be short. A flat drainage way gradient has the opposite effect. The time of concentration for small watersheds with various lengths and drainage way gradients is shown in Table 17.2.

Table 17.2 Time of concentration for small watersheds (min)

Maximum length of flow (ft)	Drainage way gradient (slope), %					
	0.05	0.10	0.50	1.00	2.00	5.00
500	18	13	7	6	4	3
1000	30	23	11	9	7	5
2000	51	39	20	16	12	9
4000	86	66	33	27	21	15
6000	119	91	46	37	29	20
8000	149	114	57	47	36	25
10,000	175	134	67	55	42	30

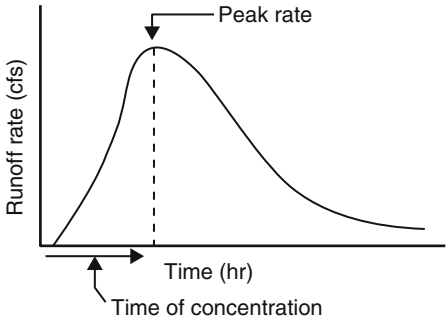

Fig. 17.4 Determining time of concentration

The rational method equation has three variables, C, I, and A. A value must be determined for each one before the equation can be used. The value of C is determined using Table 17.1. The value of I is more complex. To determine I the rainfall intensity–duration–recurrence interval Fig. 16.8 is used. To find rainfall intensity from this graph, the duration and recurrence interval must be known. In the rational method, the duration is determined from the time of concentration. The time of concentration is the amount of time that occurs from when the rainfall starts until the peak rate or runoff occurs, Fig. 17.4.

Once the time of concentration is determined from Table 17.2 and the desired recurrence interval is known, Fig. 16.8 can be used to determine the rainfall intensity.

Problem Determine the peak runoff for a watershed consisting of 90.0 acres of pasture with tight clay soil and an average slope of 4.0%. The drainage way for the watershed is approximately 4000 ft with a gradient of 0.50%. Assume a recurrence interval of 10 years.

Table 17.3 "*C*" value for sample problem

Topography, vegetation, and slope	Soil texture		
	Sandy loam	Clay and silt loam	Tight clay
Woodland			
Flat 0–5%	0.10	0.30	0.40
Rolling 5–10%	0.25	0.35	0.50
Hilly 10–30%	0.30	0.50	0.60
Pasture			
Flat 0–5%	0.10	0.30	0.40
Rolling 5–10%	0.16	0.36	0.55
Hilly 10–30%	0.22	0.42	0.60
Cultivated			
Flat 0–5%	0.30	0.50	0.60
Rolling 5–10%	0.40	0.60	0.70
Hilly 10–30%	0.52	0.72	0.82

The correct value for "*C*" is 0.40

Table 17.4 Time of concentration value for sample problem

Maximum length of flow (ft)	Drainage way gradient (slope), %					
	0.05	0.10	0.50	1.00	2.00	5.00
500	18	13	7	6	4	3
1000	30	23	11	9	7	5
2000	51	39	20	16	12	9
4000	86	66	33	27	21	15
6000	119	91	46	37	29	20
8000	149	114	57	47	36	25
10,000	175	134	67	55	42	30

The time of concentration is 33 min

Solution To determine the solution, a value must be determined for each on the three variables in the rational equation using Tables 17.1 and 17.2 and Fig. 16.8. The correct numbers to use for this example problem are shown in Tables 17.3 and 17.4, and Fig. 17.5.

The rainfall intensity (I) is 4.5 in/hr.

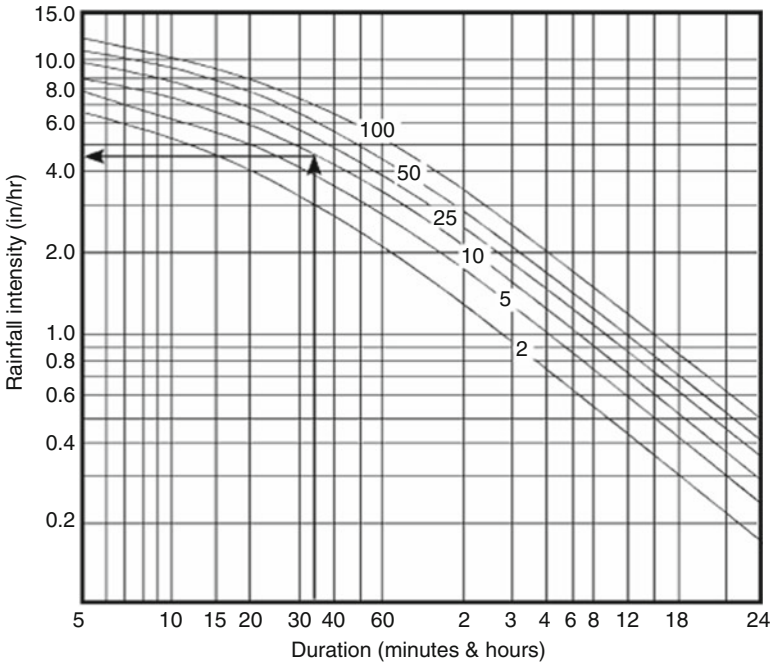

Fig. 17.5 Rainfall intensity value for sample problem

With $C = 0.40$, $I = 4.5$ in/hr, and $A = 90$ ac, the peak rate of runoff is:

$$Q = CIA = 0.40 \times 4.5 \frac{\text{in}}{\text{hr}} \times 90 \text{ ac} = 162 \frac{\text{ft}^3}{\text{sec}}$$

In this example the best estimate of the peak runoff rate is 162 cubic feet per second. Note that the units do not cancel in the equation. This is because the C value is determined so that the answer is in cubic feet per second.

17.5 Effect of Varying Recurrence Interval

The choice of recurrence interval will have a great influence on the peak rate of runoff to be expected from a watershed. This is illustrated by the following example.

Problem Given the same watershed as the previous example, calculate the peak runoff rate for recurrence intervals of 2, 5, 10, 25, 50, and 100 years.

Solution Table 17.5.

Table 17.5 Effect of varyingrecurrence interval

Recurrence interval (yr)	Time of concentration (min)	Rainfall intensity (in/hr)	Runoff coefficient (C)	Watershed area (ac)	Peak runoff rate (cfs)
2	33	3.0	0.40	90	108
5	33	3.8	0.40	90	137
10	33	4.5	0.40	90	162
25	33	5.5	0.40	90	198
50	33	6.3	0.40	90	227
100	33	7.0	0.40	90	252

17.6 Mixed Watersheds

The previous examples were the simplest kind because the watershed had the same slope, vegetation, and soil conditions. In nature, this only occurs for very small areas. Watersheds usually contain different slopes, vegetation, soil types, and farming practices. All of these variables affect the value used for C. Any changes in the value used for C will change the calculated runoff. To cope with a variable watershed, it is necessary to calculate the weighted runoff coefficient (C_w) for the watershed.

The weighted runoff coefficient is determined by finding the appropriate value of C for each field or portion of the watershed that is different, multiplying that value of C by the appropriate area (ac), adding up these products for all of the different areas in the watershed, and then dividing the sum by the total watershed area.

Study Fig. 17.6 and the following equation:

$$C_w = \frac{(A_1C_1) + (A_2C_2) + \cdots + (A_nC_n)}{\Sigma A}$$

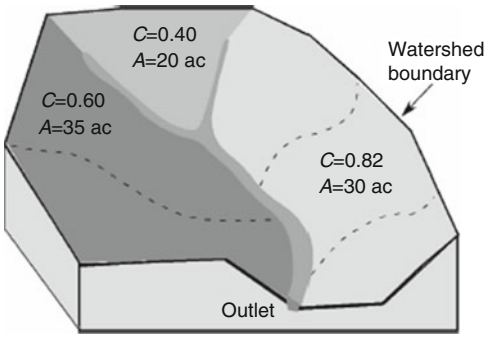

Fig. 17.6 Example of a mixed watershed

Problem Determine the weighted C for the watershed in Fig. 17.6.

Solution

$$\begin{aligned} C_w &= \frac{(A_1C_1) + (A_2C_2) + (A_3C_3)}{\Sigma A} \\ &= \frac{(35 \times 0.60) + (20 \times 0.40) + (30 \times 0.82)}{35 + 20 + 30} \\ &= \frac{21 + 8 + 24.6}{85} \\ &= \frac{53.6}{85} \\ &= 0.6305 \ldots \text{or } 0.63 \end{aligned}$$

The weighted C value for this watershed is 0.63.

17.7 Metric Problems

The rational method was developed during the 1880s in the United States using standard units. For use with metric units, the user has two options. The first one is to use the standard data and convert the answer from cubic feet per second to cubic meters per second by dividing by 360. This results in the equation:

$$Q\left(\frac{\text{m}^3}{\text{sec}}\right) = \frac{CIA}{360}$$

where Q = peak flow, m^3/s; A = drainage area, ha; C = runoff coefficient, weighted; I = rainfall intensity, mm/hr; 360 = conversion constant.

The second method is to use tables and graphs with metric units. When this method is used, the coefficient of runoff is taken from Table 17.6.

The time of concentration is found in Table 17.7.

The rainfall intensity is taken from Fig. 17.7.

Table 17.6 Recommended coefficient of runoff values for various selected land uses, SI units

Land use	Description	Hydrologic soils group[a]			
		A	B	C	D
Cultivated land	Without conservation treatment	0.49	0.67	0.81	0.88
	With conservation treatment	0.27	0.43	0.67	0.67
Pasture or range land meadow	Poor condition	0.38	0.63	0.78	0.84
	Good condition	–	0.25	0.51	0.65
	Good condition	–	–	0.41	0.61
Wood or forest land	Thin stand, poor cover, no mulch	–	0.34	0.59	0.70
	Good cover			0.45	0.59
Open spaces, lawns, parks, golf					
Courses, cemeteries					
Good condition	Grass cover on 75% or more	–	0.25	0.51	0.65
Fair condition	Grass cover on 50–75%	–	0.45	0.63	0.74
Commercial and business area	85% impervious	0.84	0.90	0.93	0.96
Industrial districts	72% impervious	0.67	0.81	0.88	0.92
Residential	Average % impervious				
Average lot size (acres)					
1/8	65	0.59	0.76	0.86	0.90
1/4	38	0.29	0.55	0.70	0.80
1/3	30	–	0.49	0.67	0.78
1/2	25	–	0.45	0.65	0.76
1	20	–	0.41	0.63	0.74
Paved areas	Parking lots, roofs, driveways, etc.	0.99	0.99	0.99	0.99
Streets and roads	Paved with curbs and storm sewers	0.99	0.99	0.99	0.99
	Gravel	0.57	0.76	0.84	0.88
	Dirt	0.49	0.69	0.80	0.84

Note: Values are based on NRCS (formerly the SCS) definitions and are average values
Source: Technical Manual for Land Use Regulation Program, Bureau of Inland and Coastal Regulations, Stream Encroachment Permits, New Jersey Department of Environmental Protection
[a]Group A soils: High infiltration (low runoff). Sand, loamy sand, or sandy loam. Infiltration rate >0.3 inch/hr when wet
Group B soils: Moderate infiltration (moderate runoff). Silt loam or loam. Infiltration rate 0.15–0.3 inch/hr when wet
Group C soils: Low infiltration (moderate to high runoff). Sandy clay loam. Infiltration rate 0.05–0.15 inch/hr when wet
Group D soils: Very low infiltration (high runoff). Clay loam, silty clay loam, sandy clay, silty clay, or clay. Infiltration rate 0–0.05 inch/hr when wet

Table 17.7 Time of concentration (minutes) SI units

Drainage way change in elevation (m)	Drainage way length (m)							
	100	150	200	250	500	1000	1500	2000
1	4	6	8	11	23	55	85	120
2	3	4.5	6.5	8	18	40	65	95
5	2	3	4.5	6	13	29	44	65
10	1.5	2.4	3.5	4.5	9	22	36	50
15	1.25	2	3	4	8	20	33	42
20	0.25	1.75	2.5	3.5	7	17	27	40

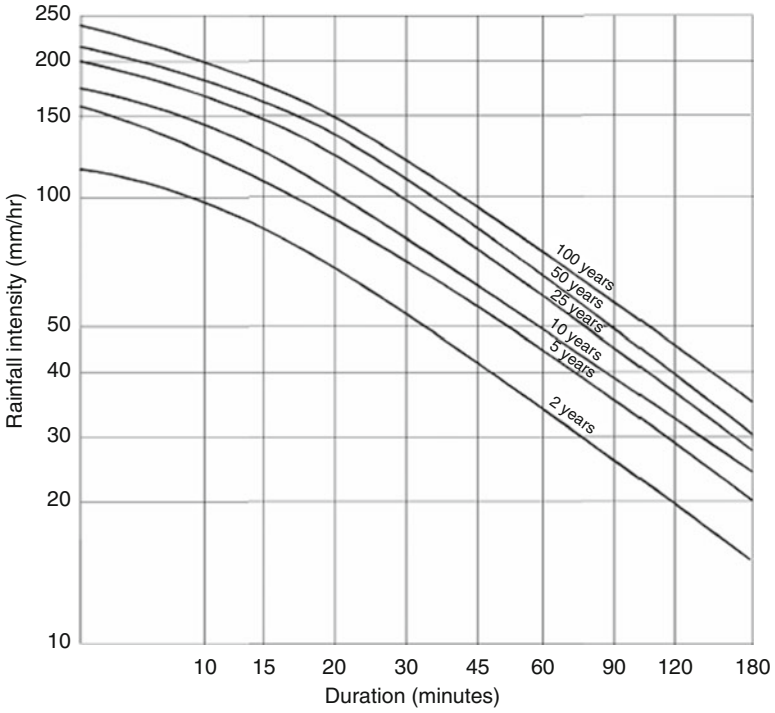

Fig. 17.7 Rainfall intensity, duration, and frequency for metric units

Problem Determine the peak rate of runoff for a 50 hectare cultivated field with conservation practices and soil group B. The drainage way has a change of elevation of 2 m and a length of 1000 m. The design calls for a 25-year storm.

Solution

$$\begin{aligned} Q\left(\frac{\mathrm{m}^3}{\mathrm{sec}}\right) &= CIA \\ &= 0.43 \times 80 \times 50 \\ &= 1,720\,\frac{\mathrm{m}^3}{\mathrm{sec}}. \end{aligned}$$

Chapter 18
Erosion and Erosion Control

18.1 Objectives

1. Understand the development of soil.
2. Understand the causes of erosion.
3. Be able to identify the two types of erosion.
4. Determine the rate of erosion using the Universal Soil Loss Equation.
5. Be able to explain common erosion control practices.

18.2 Introduction

Soil is a complex, constantly changing resource. It affects the life of plants and thereby all animals, and it is affected by plants and animals. Soil is the primary medium of growth for plants. It supplies nutrients, water, and a place to anchor roots. Soil has an economic value and therefore any that is lost from production is an economic loss. The topsoil has the most value because it is the primary source of nutrients, chemicals, seeds, water-holding capacity, and organic matter. Soil is formed from the erosion of rocks, but its value for plants and animals can be also be destroyed by erosion. In this chapter, soil development, destruction, and conservation will be discussed.

18.3 Soil Development

Soil develops from the breakdown or geological erosion of sedimentary or volcanic parent material. As the forces of nature, wind, water, heat, and cold, erode the parent material, the particle size gradually decreases, and nutrients, water, and organic matter are mixed in. This mixture is called soil. The exact rate of breakdown is debatable, but one estimate is that it takes 100 to as long as 1000 years to develop 1 inch, 25.4 mm, of topsoil.

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18.4 Causes of Soil Erosion

Soil erosion is a natural process. Rivers flood and erode the banks; intense storms cause excessive runoff, which erode soil and leave it in waterways or ponds. Wind moves soil particles. The concern about soil erosion is based on the fact that many of mankind's activities accelerate the natural process. The productivity of soil is destroyed by man-made or man-accelerated erosion that occurs from poor agricultural and construction practices. Land with permanent vegetation is very stable, but as soon as vegetation is removed, the soil is exposed to rainfall and other forces of nature. This exposure accelerates erosion. Activities such as the construction of roads and buildings, cultivation of fields, and timber harvesting all remove the natural protective cover. The two agents of erosion, water and wind, will be discussed in the next section. A method will be explained for estimating the amount of soil that is lost by water erosion.

18.5 Two Types of Erosion

For agricultural enterprises two types of erosion are a concern; water and wind.

18.5.1 Water

The amount of erosion caused by water is dependent on four factors: climate, soil, vegetation, and topography. These four factors determine what type of erosion occurs and how much occurs.

18.5.1.1 Climate

The impact of climate on soil erosion is related to the amount and the intensity of rain. The greater the annual rainfall, the greater the potential will be for soil erosion. The greater the intensity of the rainfall, the greater the potential will be for soil erosion. As the frequency of intense storms increases, the greater the potential will be for water erosion. Regions of the earth with frequent, intense rainfall or a large volume of annual rainfall have a greater potential for water-caused soil erosion than arid regions.

18.5.1.2 Soil

The contribution of soil to erosion relates to the size of the soil particles and the moisture content of the soil. Sandy and organic soils have the greatest potential for water erosion. These soils are not bound together, especially when wet, and the soil particles are easily moved by water.

18.5.1.3 Vegetation

The role of vegetation in soil water erosion is based on energy. Raindrops striking the soil surface contain sufficient energy to propel soil particles into the air. When rain drops strike vegetation, the vegetation adsorbs some or all of the energy thus reducing the impact on the soil. Vegetation and the roots of plants also help bind the soil together and help it resist the energy of flowing water. In cultivated fields, crop residues in and on the soil provide the same function as natural vegetation. The amount of crop residues can be measured by randomly laying out a 100 f. tape across a field and counting the number of 1 foot marks that are over or touching residue. This number is the residue cover as a percent. If four of the foot marks are over a piece of residue, then the percent is 4%. The recommended minimum percentage is based on the location and the soil type.

18.5.1.4 Topography

The influence of topography on soil erosion is associated with the slope of the land. Water flowing down slope has energy. The amount of energy is determined by the velocity of the water and the length of the slope. Water flowing down a steep slope will have more energy than water flowing down a flat slope. Higher velocity water will have more energy than slow-moving water. The greater the amount of energy in the water, the greater the potential for erosion.

These four factors determine what type of water erosion occurs and how much occurs.

18.5.1.5 Stages of Water Erosion

Water erosion usually is divided into three stages: raindrop, sheet and rill, and gully. Raindrop erosion is the soil splash resulting from the impact of water on soil particles. If the soil is covered with vegetation, raindrop erosion is almost zero. When the soil is a bare cultivated field, raindrop erosion can be significant. It is estimated that raindrops can displace soil particles 2 feet vertically and 5 feet horizontally. The effect of raindrop erosion increases as the slope increases because there is greater movement down slope than there is up slope.

Sheet and rill erosion are the next two stages. They are combined because many experts believe sheet erosion only exists in theory. As the rainfall intensity exceeds the infiltration rate of the soil, water starts to move across the soil's surface in a thin sheet. Almost as soon as the movement begins, small but well-defined channels develop, which are called rills. Rills can be easily farmed over and are easy to overlook, but they account for most of the soil loss to water erosion.

Gully erosion is the next stage. Gullies are an advanced stage of rills. Small ones may still be farmed over, but if they are not checked, they become too large and then must be farmed around.

18.5.2 Wind

Movement of the soil due to wind erosion is not down the slope as in water; instead the direction is determined by the wind. When the soil is completely covered with vegetation, very little wind erosion occurs because the vegetation reduces the velocity of the wind at the surface of the soil. When the wind has access to the surface, erosion may occur. The velocity of the wind, the soil moisture, and the soil particle size determine the amount of erosion and type of erosion. The greater the wind velocity, the greater the volume and particle size the wind will be able to transport. Fine sandy soils are affected by wind more than clay soils. Dry soils are easier to erode than moist soils.

Wind erosion is not divided into types; it only varies by degree (stages). There are three stages of movement. All three stages may occur simultaneously. The first stage, suspension, occurs when soil particles are fine enough and the velocity is high enough to keep the particles suspended in the air. Very fine particles can be transported for hundreds of miles. The second stage is skipping and bouncing, or saltation. This state of wind erosion accounts for the largest volume of soil movement. In saltation, the wind is strong enough to pick up the soil particle, but not strong enough to hold them in suspension. The wind lifts up the particles and carries them for a short distance, but then they are dropped. The third stage is rolling or creep. In the creep stage, the wind moves or rolls the soil particles across the surface of the soil, but it does not pick them up.

The five factors used to estimate wind erosion are soil erodibility, climate, soil roughness, field length, and vegetation. To estimate the amount of wind erosion for a specific location, contact the National Resource Conservation Service (NRCS).

18.6 Estimating Soil Loss

Equations have been developed to estimate the amount of soil loss to water and wind erosion. These are called the Universal Soil Loss Equation (USLE) for water and the Wind Erosion Equation (WEQ) for wind. The USLE for water has been updated, and the new version is called the Revised Universal Soil Loss Equation (RUSLE). Another version, RUSLE2, is a computer program. The WEQ is a computer program that can be utilized through a NRCS office. The USLE for water is:

$$A = R \times K \times L \times S \times C \times P$$

where A = predicted average annual soil loss, T/ac/yr; R = rainfall factor; K = soil erodibility factor; L = slope length factor; S = slope gradient factor; C = cropping management factor; P = erosion control practice factor.

For this discussion, several of these factors will be combined to give the following equation:

$$A = R \times K \times LS \times CP$$

The USLE assigns numerical values to the factors that influence water erosion. Therefore, the accuracy of the calculated soil loss is only as good as the numerical values representing these factors. The tables and graph included here are generalized to show the influence of the different factors and to aid in the understanding of the equation. These values should not be used for the design of soil conservation structures or for estimating soil loss for government programs. More accurate values for specific areas can be obtained from the NRCS or similar agency.

18.6.1 Rainfall Factor (R)

The rainfall factor is a measure of the intensity and duration of the expected rainfall events. Common values for R range from 100 to 350. A higher number should be used in an area of high annual rainfall and high rainfall intensities. Numbers are available for specific locations from government sources.

18.6.2 Soil Erodibility (K)

The *K* value is a measure of the soil's susceptibility to erosion. The soil's texture, organic matter content, and permeability influence the *K* value. The values are based on a cultivated, continuous fallow arbitrary field with a slope length of 72.6 ft and a slope of 9%. Typical values for some soils and organic matter contents can be found in Table 18.1.

18.6.3 Topographic Factor (LS)

The topographic factor is a measure of the expected soil loss for the field compared to the arbitrary field with a slope length of 72.6 ft and a slope of 9%. It is a combination of the slope length and the percent of slope. An estimate for *LS* can be found in Fig. 18.1.

Table 18.1 Soil erodibility factor (K) (ton/ac)

Textural class	Organic matter content %		
	0.5	2.0	4.0
Fine sand	0.16	0.14	0.10
Very fine sand	0.42	0.36	0.28
Loamy sand	0.12	0.10	0.08
Loamy very fine sand	0.44	0.38	0.30
Sandy loam	0.27	0.24	0.19
Very fine sandy loam	0.47	0.41	0.33
Silt loam	0.48	0.42	0.33
Clay loam	0.28	0.25	0.21
Silty clay loam	0.37	0.32	0.26
Silty clay	0.25	0.23	0.19

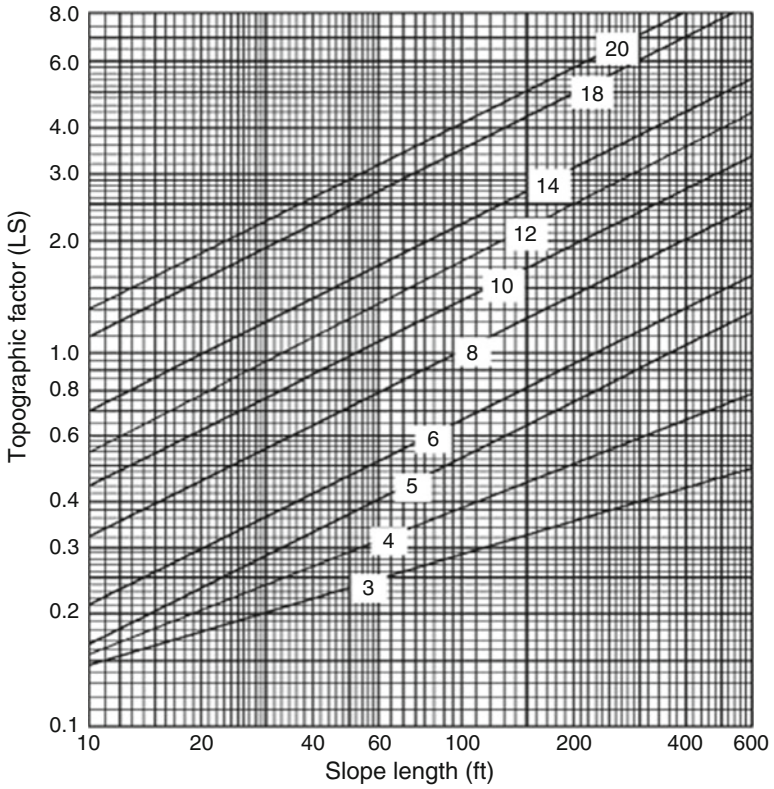

Fig. 18.1 Typical topographic factors (LS) for slopes of 3–20% and slope lengths of 10–600 ft

Table 18.2 Typical cropping and management factors (*CP*)

Management factors	Cropping practices		
	Up and down the slope	Terraces and field boundary	On the contour
Continuous small grain MRU (6/20)	0.29	0.21	0.15
Continuous small grain HRU (6/20)	0.22	0.16	0.11
Continuous small grain MRU (8/1)	0.22	0.16	0.11
Continuous small grain HRU (8/1)	0.18	0.13	0.09
Continuous small grain ROS	0.12	0.09	0.06
Continuous cotton MF no WC	0.59	0.42	0.30
RC Continuous grain sorghum (25–30 bu)	0.48	0.34	0.24
RC Continuous grain sorghum (35–45 bu)	0.42	0.30	0.21
Continuous peanuts with WC	0.43	0.30	0.22
Continuous peanuts no WC	0.54	0.38	0.27
Alfalfa 5 yr./small grain 2 yr	0.05	0.05	0.05

MRU moderate residue turned under, *HRU* heavy residue turned under, *RC* row crop, *ROS* residue on surface at seeding time, *MF* moderate fertilizer, *WC* winter cover

18.6.4 Cropping and Management Factor (CP)

The original USLE separated the cropping factor (C) and management factor (P) into two different terms. In this discussion, they have been combined. The cropping factor is used to estimate the relative effectiveness of the practice to retard soil loss when compared to a continuously tilled field. The management factor (P) is an estimation of the effect of conservation practices in reducing soil loss. These factors combined are a function of the crop raised, the management practice, the planting date, the amount of residue on the surface, and the tillage practice. Values representing these factors can be found in Table 18.2.

Problem Estimate the annual erosion for a field having a rainfall factor of 220, consisting mainly of loamy sand with 2% organic matter and averaging a 4% slope with a slope length of 400 ft, which has been in continuous small grain, normally planted in June, with moderate residue worked under and farmed up and down the slope.

Solution Using the USLE and the appropriate tables and figure:

$$A = R \times K \times LS \times CP$$

where $R = 220$; $K = 0.10$, Table 18.3.
$LS = 0.69$, Fig. 18.2.
$CP = 0.29$, Table 18.4.

$$A = R \times K \times LS \times CP = 220 \times 0.10 \times 0.69 \times 0.29$$
$$= 4.4022 \text{ or } 4.4\,\mathrm{T/ac/yr}$$

Table 18.3 *K* factor for sample problem

	Organic matter content %		
Textural class	0.5	2.0	4.0
Fine sand	0.16	0.14	0.10
Very fine sand	0.42	0.36	0.28
Loamy sand	0.12	0.10	0.08
Loamy very fine sand	0.44	0.38	0.30
Sandy loam	0.27	0.24	0.19
Very fine sandy loam	0.47	0.41	0.33
Silt loam	0.48	0.42	0.33
Clay loam	0.28	0.25	0.21
Silty clay loam	0.37	0.32	0.26
Silty clay	0.25	0.23	0.19

The correct *K* factor is 0.10

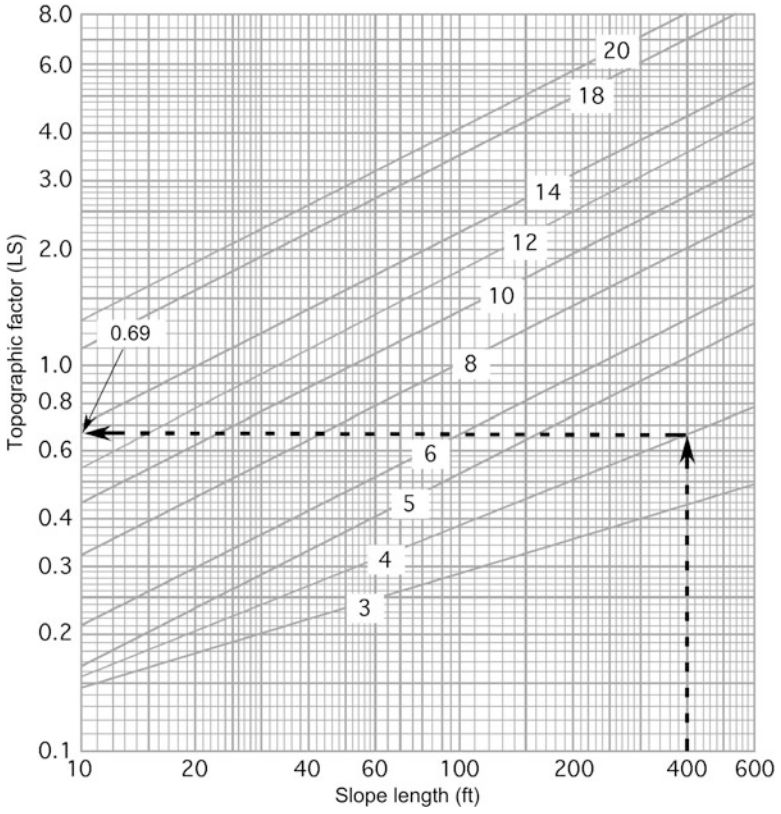

Fig. 18.2 *LS* for sample problem

Table 18.4 *CP* value for *sample* problem

Management factors	Cropping practices		
	Up and down the slope	Terraces and field boundary	On the contour
Continuous small grain MRU (6/20)	0.29	0.21	0.15
Continuous small grain HRU (6/20)	0.22	0.16	0.11
Continuous small grain MRU (8/1)	0.22	0.16	0.11
Continuous small grain HRU (8/1)	0.18	0.13	0.09
Continuous small grain ROS	0.12	0.09	0.06
Continuous cotton MF no WC	0.59	0.42	0.30
RC Continuous grain sorghum (25–30 bu)	0.48	0.34	0.24
RC Continuous grain sorghum (35–45 bu)	0.42	0.30	0.21
Continuous peanuts with WC	0.43	0.30	0.22
Continuous peanuts no WC	0.54	0.38	0.27
Alfalfa 5 yr./small grain 2 yr	0.05	0.05	0.05

MRU moderate residue under, *HRU* heavy residue under, *RC* row crop, *ROS* residue on surface at seeding time, *MF* moderate fertilizer, *WC* winter cover

18.7 Erosion Control

The best philosophy for erosion control is that it is better to prevent erosion than to try to correct it. There is no best solution for erosion control that will work in all situations. Erosion prevention and control must be developed for each site using the resources that are available.

On cultivated land, the best methods to use are those activities that will reduce the effect of wind and water on the soil particles. For the prevention of water erosion, it is important to provide as much protection as possible to the surface of the soil. This includes management of tillage practices to leave residue on the surface and the use of cover crops in nonproductive seasons. Additional protection is provided by reducing the length of the continuous slope by installing terraces. To illustrate the effect of these practices, rework the sample problem with the appropriate values for terraces and residue.

Problem Estimate the annual erosion for a field that has a rainfall factor of 220, consists mainly of loamy sand with 2% organic matter, averages a 4% slope with a slope length of 200 ft, and has been in continuous small grain with heavy residue, normally planted in June, and farmed with terraces.

Solution

$$A = R \times K \times LS \times CP = 220 \times 0.10 \times 0.69 \times 0.21 = 3.187 \text{ or } 3.2 \text{ T/ac/yr.}$$

In the original problem, the soil loss was 4.4 T/ac/yr. With the modifications the soil loss is 3.2 T/ac/yr, a reduction of 27%.

Residues on the surface also help prevent wind erosion, but reducing the length of the slope does not. The critical factors for preventing wind erosion, other than residue, are the roughness of the surface and the unobstructed distance that the wind

can blow. Reducing the unobstructed distance is an effective control. This explains the prevalent use of shelterbelts in the Great Plains region. A shelterbelt will provide protection downwind for up to 10 times its height.

Other methods are appropriate for the control of both water and wind on small areas for a short duration, such as construction sites. A common practice is to use commercial silt fences, bales of straw, or nets to help prevent soil from leaving the site. Installing temporary wind barriers and keeping the ground covered can control wind erosion.

18.8 Metric Problems

This version of the USLE is only available in standard units and was included to illustrate the factors that affect soil erosion. Versions of the Revised Universal Soil Loss Equation (RUSLE) are available on the World Wide Web using metric units.

Chapter 19
Irrigation

19.1 Objectives

1. Understand the purpose and use of irrigation.
2. Be able to describe the common irrigation systems.
3. Be able to calculate the required system capacity.
4. Be able to determine the irrigation interval and the depth of water to apply.

19.2 Introduction

The most limiting and most variable environmental factor affecting the productivity of plants is water. Whenever adequate water is not available, farmers have always tried to remedy the situation by irrigating their crops. Historically water supplies for agriculture have been sufficient to meet the demands for irrigation. The challenge has been that the location of the water is not always close to where it is needed. This requires pumps, dams, canals, and other water structures to store and transport the water to where it is needed.

Today the demands for water exceed the supply. Irrigators must spend more resources, because the costs have increased, to maintain their share of a declining supply of water. Even where it is available, pumping and/or transportation costs have increased dramatically in many locations. Today the profitability of irrigated agriculture is dependent of efficient use of water. The effective and efficient use of irrigation is dependent on four factors.

1. The effect of irrigation on plant production
2. The best system for a given field and water supply
3. Determining how much water to apply at peak use rate and when to apply it
4. The quality of the water

This chapter will discuss these aspects of irrigation.

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19.3 The Effect of Irrigation

Agricultural plants need warm temperatures, sunlight, nutrients, and water to grow. In many regions of the world, the required temperature and sunlight are available, but water is not. All plants have a minimum annual water requirement to survive and an optimum annual water requirement for maximum production. Historically, the availability of water has determined where crops can be grown. A high demand crop, such as rice, could not be grown in a region that has a low annual rainfall. In addition, whenever the water available to the plant is less than the optimum amount, the production is reduced. The application of water through irrigation can provide the missing requirement for plant growth. The result of irrigation is that the area where some crops can be grown is expanded and the production of all crops is increased by supplementing rainfall.

19.4 Irrigation Systems

Once the decision has been made to irrigate, the next consideration is what type of system to use. Water is applied in one of three ways: from above the ground, on the ground surface, or from below the surface. The choice usually is based on cost and topography. This section will review the basic types of irrigation systems.

19.4.1 Above Ground

The most common aboveground irrigation system is the sprinkler. In sprinkler systems, water is injected into the air by one of the three types of nozzles: spray, rotor, or impact. Sprinkler systems can be used on any land that can be cultivated. Sprinklers may be solid set (in a permanent position), movable, or mobile. The common means of movement are (1) manual–lawn sprinkler or pipe system; (2) tractor-moved–skid or wheel-mounted system; (3) self-moved–side wheel roll or big gun system; and (4) self-propelled–center pivot and lateral move system. Different modifications and variations of these systems are used. The best system depends on the topography, shape, and size of the field, the amount and cost of labor for movement, and the value added for the crop. For sprinkler systems, it is important that the application rate not exceed the infiltration rate of the soil.

19.4.2 Surface

In surface irrigation, water is made available to plants by allowing it to flow over the surface by gravity or through drip valves (a process called trickle or drip irrigation). The common gravity systems are flood and furrow. Flood systems require relatively flat land, and the water is distributed in level borders or contoured levees. Land for furrow irrigation can have a small slope. The water is added to the furrows at the top of the slope and allowed to flow down the furrows. For level borders and contoured levees, the water usually is delivered by surface ditch. Ditches can deliver water for furrows, but a gated pipe or a siphon tube is also used. As a general rule, gravity systems require more labor than sprinkler systems to maintain the ditches and the dikes, move the gated pipe, and control the flow of the water.

In trickle irrigation, drip valves or emitters are located along a line at uniform spacing or at each large plant. These systems have high application efficiency because a very small amount of water is applied and it is applied directly to the plant.

19.4.3 Subsurface

The two most common subsurface irrigation systems are a porous pipe buried in the root zone and a trickle system buried alongside the plants.

19.5 Depth of Water to Apply

Seasonal water demand and peak daily use vary considerably from crop to crop and from one field to the next. When to irrigate and how much water to apply are the two most difficult decisions to make in managing irrigation systems. Many different methods have been developed to help answer these two questions. The following discussion will explore some of the factors influencing these decisions and present one method for determining how much water to apply and the irrigation interval.

The amount of water used by plants depends on five factors:

1. The length of the growing season
2. The amount of daylight per day
3. The daily temperature
4. The speed and direction of the wind
5. The crop's stage of growth

For any given plant, the daily rate of use will increase until the plant reaches maturity, and then it will decrease, Fig. 19.1. The peak water use rate occurs at the height of the growing season. Table 19.1 shows the peak use for a number of crops with both short and long growing seasons and the root zone depth from which each crop extracts most of its moisture.

Two characteristics of soil must be considered in determining how much water should be applied: (1) the rate at which soil can absorb water, the infiltration rate, and (2) the total amount of water that can be stored. The infiltration rate is determined by the soil texture, and the total amount of water that can be stored is determined by the soil texture and soil depth. Loams and clays can hold more water than sands, as shown in Table 19.2. Also note that the type and the depth of subsoil make a difference in the amount of water that can be stored per irrigation. For example, soils having more compact subsoil can store a greater amount of water than the same soils having a uniform depth.

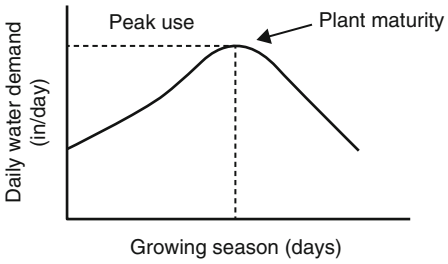

Fig. 19.1 Typical daily water demand

Table 19.1 Root zone depth and peak water use rate

Crop	Length of growing season		
	Root zone depth of principle moisture extraction (in)	180–210 days peak use (in/day)	210–250 days peak use (in/day)
Alfalfa	48	0.29	0.32
Beans	24	0.20	0.20
Corn	36	0.30	0.35
Cotton	36	–	0.28
Grain sorghum	30	0.20	0.20
Melons	30	0.20	0.22
Other truck	24	0.20	0.22
Pasture	24	0.28	0.30
Peas	36	0.19	–
Potatoes	24	0.38	0.20
Small grain	30	0.20	0.22
Sugar beets	36	0.28	0.30
Tomatoes	48	0.20	0.22
Vineyards	48	0.22	0.25

Table 19.2 Net amount of water to store per irrigation

Soil profile	Net amount of water to store (in) for various root zone depths			
	24 in	30 in	36 in	48 in
Coarse sandy soil, uniform to 6 ft	0.85	1.10	1.30	1.75
Coarse sandy soil over compacted subsoil	1.50	1.75	2.00	2.50
Fine sandy loam uniform to 6 ft	1.75	2.20	2.60	3.00
Fine sandy loam over compacted subsoil	2.00	2.40	2.80	3.25
Silt loam uniform to 6 ft	2.25	2.75	3.00	4.00
Silt loam over compacted subsoil	2.50	3.00	3.25	4.25
Heavy clay or clay loam soil	2.00	2.40	2.85	3.85

The rooting depth of the crop also influences the amount of water that should be stored. Any water that infiltrates into the soil to a depth below the root zone is lost to the plant. These factors were taken into consideration during the development of Tables 19.1 and 19.2.

To use these tables, first consult Table 19.1 for a particular crop and growing season length and obtain values for (1) the root zone depth of principal moisture extraction and (2) the peak daily water use. Then Table 19.2 can be used to determine the number of inches of water to store per irrigation. Note that you must know the soil type or profile on which the irrigation is to take place and the root zone depth of principal moisture extraction of the crop.

Problem What are the root zone depth, peak daily use, and net amount of water to store per irrigation for a crop of corn grown on a location where the season is greater than 210 days on a silt loam soil over compacted subsoil?

Solution Use Tables 19.1 and 19.2. The values for root zone depth and peak daily use are shown in Table 19.3.

Table 19.3 Values for root zone depth and peak daily use for problem

Crop	Length of growing season		
	Root zone depth of principle moisture extraction (in)	180–210 days peak use (in/day)	210–250 days peak use (in/day)
Alfalfa	48	0.29	0.32
Beans	24	0.20	0.20
Corn	36	0.30	0.35
Cotton	36	–	0.28
Grain sorghum	30	0.20	0.20
Melons	30	0.20	0.22
Other truck	24	0.20	0.22
Pasture	24	0.28	0.30
Peas	36	0.19	–
Potatoes	24	0.38	0.20
Small grain	30	0.20	0.22
Sugar beets	36	0.28	0.30
Tomatoes	48	0.20	0.22
Vineyards	48	0.22	0.25

Root zone depth = 36 in.
Peak daily use = 0.35 in/day.

Using Table 19.4, the net amount of water to store per irrigation is 3.25 inches.

Next determine the amount of water to apply. The amount of water to apply must be greater than the amount to store because irrigation systems do not operate at 100% efficiency. Some of the water will evaporate, some runs off, and some percolates below the crop root zone. The term application efficiency is used to describe these losses. It is defined as the ratio of the depth of water stored to the depth of water applied, expressed as a percent. The application efficiency of a well-designed irrigation system will be between 60% and 80%. Application efficiency can be used to determine the amount of water to apply in the following manner.

Table 19.4 Net amount of water to store for sample problem

Soil profile	Net amount of water to store (in) for various root zone depths			
	24 in	30 in	36 in	48 in
Coarse sandy soil, uniform to 6 ft	0.85	1.10	1.30	1.75
Coarse sandy soil over compacted subsoil	1.50	1.75	2.00	2.50
Fine sandy loam uniform to 6 ft	1.75	2.20	2.60	3.00
Fine sandy loam over compacted subsoil	2.00	2.40	2.80	3.25
Silt loam uniform to 6 ft	2.25	2.75	3.00	4.00
Silt loam over compacted subsoil	2.50	3.00	3.25	4.25
Heavy clay or clay loam soil	2.00	2.40	2.85	3.85

$$\text{Depth of water to apply} = \frac{\text{Depth of water stored (in)}}{\text{Application efficiency}}$$

or

$$\text{DWA} = \frac{\text{DWS}}{\text{AE}}$$

where DWA = depth of water to apply, in; DWS = depth of water to store, in; AE = application efficiency, as a decimal.

Problem How much water should be applied for the corn crop in the previous problem if the application efficiency is 70%?

Solution

$$\text{DWA} = \frac{\text{DWS}}{\text{AE}} = \frac{3.25\,\text{in}}{0.70} = 4.642\ldots\text{or } 4.64\,\text{in}$$

It is also necessary to determine an irrigation interval, which is the number of days it takes the crop to use up the water stored in the soil. The irrigation interval is determined by dividing the amount of water stored in the soil by the plants daily use. For peak use the irrigation interval is:

$$\text{IRI} = \frac{\text{DWS}}{\text{PDU}}$$

where IRI = irrigation interval, days; DWS = depth of water to store, in; PDU = peak water use, in/day.

Problem What is the irrigation interval for the corn crop in the previous problem?

Solution

$$\text{IRI} = \frac{\text{DWS}}{\text{PDU}} = \frac{3.25\ \text{in}}{0.35\ \frac{\text{in}}{\text{day}}} = 9.285\ldots\text{or } 9.3\ \text{day}$$

For this corn crop, if 3.25 inches of water is stored in the soil per irrigation, at the time of peak use, it must be irrigated every 9.3 days.

If there is rainfall during the irrigation period, the irrigation interval should be adjusted accordingly. For example, if 1.25 inches of rain fell on the corn crop in the previous problem, then we would divide the amount of rain (in) by the water needs of the crop (in/day) and extend the interval in the corresponding number of days. For the peak demand of the corn crop, $1.25 \div 0.35 = 3.6$ days. Instead of irrigating again in 9.3 days, the irrigation interval could be extended to 12.9 or 13 days.

19.6 System Capacity

System capacity is the maximum amount of water that an irrigation system can deliver on a continuous basis. Different units are used to describe system capacity. These are acre-feet (ac-ft, i.e., the amount of water it will take to cover one acre, 1 foot deep),

acre-inch (ac-in), gallons per minute (gal/min or gpm), and cubic feet per second (ft^3/sec or cfs). The required pumping capacity of an irrigation system depends on the area to be irrigated (ac), the depth of water to apply (in), and the length of time that the irrigation system is operated (hr). Length of operation time refers to pumping time, not clock time. Pumping time is only the time water is flowing.

The amount of time per day that an irrigation system can operate depends on the type of system and the amount of maintenance it requires. A self-propelled unit may be able to run several days without stopping, whereas manual-moved, tractor-towed, and self-moved systems must be shut down at regular intervals so they can be moved. For systems other than center pivots and lateral moves, only a portion of a field is irrigated at one time, and time is required to move the system from one portion of the field "set" to another "set." The term irrigation period is used to designate the number of days that a system can apply the water for one irrigation to a given area. Note that it is necessary for the irrigation period to be equal to or less than the irrigation interval. The required capacity of a system, in gallons per minute, can be determined by the following equation:

$$\text{RSC} = \frac{453 \times A \times \text{DWA}}{\text{IRP} \times \text{HPD}}$$

where RSC = required system capacity, gal/min; 453 = unit conversion constant; A = area irrigated, ac; DWA = depth of water to apply per irrigation, in; IRP = irrigation period, day; HPD = time operating, hr/day.

Problem Determine the required system capacity (gal/min) for the corn crop in the previous problem when the field area is 200 acres and the system can operate for 18.0 hr per day for 7.7 days.

Solution

$$\text{RSC} = \frac{453 \times A \times \text{DWA}}{\text{IRP} \times \text{HPD}} = \frac{453 \times 200 \text{ ac} \times 4.65 \text{ in}}{7.7 \text{ day} \times \dfrac{18.0 \text{ hr}}{\text{day}}}$$

$$= \frac{424{,}290}{138.6} = 3039.61 \text{ or } 3040 \frac{\text{gal}}{\text{min}}$$

For 200 acres of long-season corn grown on silt loam soil over compacted subsoil, irrigated with a system that is 70% efficient and limited to operating 18 h per day for 7.7 days, the system must be able to deliver 3040 gallons of water per minute.

Note: This is an example of an equation with a unit conversion constant. The same problem can be solved using the unit cancellation method.

$$\frac{\text{gal}}{\text{min}} = \frac{1 \text{ hr}}{60 \text{ min}} \times \frac{1 \text{ day}}{18 \text{ hr}} \times \frac{1}{7.7 \text{ day}} \times \frac{1 \text{ gal}}{231 \text{ in}^3} \times \frac{4.65 \text{ in}}{1}$$

$$\times \frac{144 \text{ in}^2}{1 \text{ ft}^2} \times \frac{43{,}560 \text{ ft}^2}{1 \text{ ac}} \times \frac{200 \text{ ac}}{1} = \frac{5{,}833{,}555{,}200}{1{,}920{,}996}$$

$$= 3036.7 \text{ or } 3040 \frac{\text{gal}}{\text{min}}$$

In some situations it might be necessary to use units of capacity other than gallons per minute. For example, water supplied from a large reservoir is often measured in acre-feet. In these cases, unit cancellation and/or the appropriate conversion factors (Appendix I or II) can be used to convert the units.

Problem What will the system capacity need to be in units of acre-feet/min?

Solution Using unit cancellation and system capacity from the previous problem:

$$\frac{\text{ac-ft}}{\text{min}} = 3040\,\frac{\text{gal}}{\text{min}} \times \frac{1\ \text{ft}^3}{4.48\ \text{gal}} \times \frac{1\ \text{ac}}{43{,}560\ \text{ft}^2}$$

$$= 0.009319\ldots \text{or } 9.32\,\text{E-3}\ \frac{\text{ac-ft}}{\text{min}}$$

As noted earlier, system capacity is a function of four variables: area (ac), water flow rate (gal/min, ft^3/min, ac-ft./min, etc.), depth of water applied or peak use (in), and time (min, hr., or days). This relationship is expressed mathematically as:

$$D \times A = Q \times T$$

where D = depth of water, either applied or peak use, in; A = area irrigated, ac; Q = water flow rate, cfs; T = length of time water is applied, hr.

When any three of the variables are known, the remaining one can be calculated by rearranging the equation and substituting the values of the known variables. You must enter flow rate (Q) in cubic feet per second, depth in inches, and time in hours. The following discussion will illustrate several uses of this equation.

In the previous problem, we determined the required system capacity using unit cancellation for a problem with an application efficiency of 70%. If it is necessary to know how much water has been applied, the application efficiency should not be included. When we want to know the depth of water that has been applied, D becomes the depth of water applied (D_{WA}). This will work because the unit of measure is the same for both peak use and D_{WA} (inches).

Problem A producer spends 120 hr. irrigating 90.0 acres. The pump discharges 1350 gallons per minute. What average depth of water (in) is applied?

Solution Because we want to know the amount of water applied, not the amount available to the plants, the efficiency factor is not used. Also, Q must be converted from gal/min to ft^3/sec. Rearranging the equation, substituting depth of water to apply (D_{WA}) for the depth (D), and including the conversion factor

$1\ \text{ft}^3/\text{sec} = 2.25 \times 10^{-3}\ \text{gal/min}$[1]:

$$
\begin{aligned}
D_{\text{WA}} \times A &= Q \times T \\
D_{\text{WA}} &= \frac{Q \times T}{A} \\
&= \frac{\left(\dfrac{1350 \dfrac{\text{gal}}{\text{min}} \times 2.25\ \text{E-3}\ \dfrac{\text{ft}^3}{\text{sec}}}{1 \dfrac{\text{gal}}{\text{min}}} \right) \times 120\ \text{hr}}{90\ \text{ac}} \\
&= \frac{364.5}{90} \\
&= 4.05\ \text{in}
\end{aligned}
$$

An examination of this problem shows that the units do not cancel. However, when we enter the values of the variables with the units listed above, we can obtain an answer very close to the true value. The symbol ≅ means approximately equal. The exact solution using unit conversion/cancellation is:

$$
\begin{aligned}
D_{\text{WA}} \times A &= Q \times T \\
D_{\text{WA}} &= \frac{Q \times T}{\text{A}} \\
&= \frac{\left(1350 \dfrac{\text{gal}}{\text{min}} \times 231\ \dfrac{\text{in}^3}{\text{gal}} \times \dfrac{1\ \text{ft}^3}{1728\ \text{in}^3} \right) \times 120\ \text{hr} \times 60 \dfrac{\text{min}}{\text{hr}} \times 12\ \dfrac{\text{in}}{\text{ft}}}{90\ \text{ac} \times 43{,}560\ \dfrac{\text{ft}^2}{\text{ac}}} \\
&= 3.98\ \text{in}
\end{aligned}
$$

In this case, the error in the approximate solution is:

$$
\begin{aligned}
\%\ \text{Error} &= \frac{4.05 - 3.98}{3.98} \times 100 \\
&= 1.76\%
\end{aligned}
$$

Variations occur in the use of the equation for different types of irrigation systems. In situations where the limiting factor is the availability of water, the problem is to determine the maximum area that can be irrigated with the available water supply.

Problem What is the largest size of lawn (ft^2) that can be irrigated in 12 hr if a minimum of 0.5 inch of water is applied at each irrigation, the system is 90% efficient, and the water supply delivers 3.5 gal/min?

[1] If $\dfrac{\text{ft}^3}{\text{sec}} = \dfrac{1\ \text{gal}}{\text{min}} \times \dfrac{1\ \text{min}}{60.0\ \text{sec}} \times \dfrac{1\ \text{ft}^3}{7.40\ \text{gal}} = 2.25 \times 10^{-3}\ \dfrac{\text{ft}^3}{\text{sec}}$ then $\dfrac{1\ \text{gal}}{\text{min}} = \dfrac{2.25 \times 10^{-3}\ \text{ft}^3}{1\ \text{sec}}$

Solution Rearranging the equation, adding the efficiency factor, and converting the area to square feet:

$$D \times A = Q \times T$$

$$A\left(\text{ft}^2\right) = \left(\frac{Q \times T}{D} \times \frac{1 \text{ ac}}{43{,}560 \text{ ft}^2}\right) \times 0.90$$

$$= \left(\frac{\left(3.5 \dfrac{\text{gal}}{\text{min}} \times \dfrac{60 \text{ min}}{1 \text{ hr}} \times \dfrac{1 \text{ ft}^3}{7.48 \text{ gal}}\right) \times 12.0 \text{ hr}}{\dfrac{0.5 \text{ in}}{12 \dfrac{\text{in}}{\text{ft}}}} \right) \times 0.90$$

$$= \left(\frac{336.8\ldots}{0.04167}\right) \times 0.90$$

$$= 7276.42\ldots \text{ or } 73,000 \text{ ft}^2$$

If flood irrigation is used to water a field, assuming that the water flow rate is limited, it usually is necessary to determine the amount of time that the water should flow to cover the field at the desired depth.

Problem How long will it take to apply 4 inches of water uniformly over 120 acres when the water is available at the rate of 20 cfs? (Assume 100% efficiency.)

Exact Solution

$$D \times A = Q \times T$$

$$T(\text{hr}) = \frac{D \times A}{Q}$$

$$= \frac{4.0 \text{ in} \times \dfrac{1 \text{ ft}}{12 \text{ in}} \times 120 \text{ ac} \times 43{,}560 \dfrac{\text{ft}^2}{\text{ac}}}{20.0 \dfrac{\text{ft}^3}{\text{sec}} \times 60 \dfrac{\text{sec}}{\text{min}} \times 60 \dfrac{\text{min}}{\text{h}}}$$

$$= \frac{1{,}742{,}400}{72{,}000} = 24.2 \text{ hr}$$

During furrow irrigation it is important to know how long the water must run to apply the desired amount for each set of furrows. Three values are necessary to calculate time: the water flow rate for each furrow or for the entire set, the area of the furrow or the set, and the amount of water to be applied. The area is determined from the number of rows in the set, the row spacing, and the length of the row.

Problem How much time is required to apply 3 inches of water to 60, 32 inch rows when the rows are one half mile long and the system capacity is 30 gal/min/row?

Solution

$$D \times A = Q \times T$$

$$T = \frac{D \times A}{Q}$$

A and Q are unknown and must be solved for.

$$A = \frac{\text{Number} \times \text{Spacing (ft)} \times \text{Length (ft)}}{43{,}560 \dfrac{\text{ft}^2}{\text{ac}}}$$

$$= \frac{60 \text{ rows} \times 32 \dfrac{\text{in}}{\text{row}} \times \dfrac{1 \text{ ft}}{12 \text{ in}} \times 0.5 \text{ mile} \times 5280 \dfrac{\text{ft}}{\text{mile}}}{43,560 \dfrac{\text{ft}^2}{\text{ac}}}$$

$$= 9.696 \ldots \text{ac}$$

$$Q \left(\frac{\text{ft}^3}{\text{sec}} \right) = \frac{30.0 \dfrac{\text{gal}}{\text{min}}}{\text{row}} \times 60 \text{ row} \times \frac{2.25 \text{ E} - 3 \dfrac{\text{ft}^3}{\text{sec}}}{1 \dfrac{\text{gal}}{\text{min}}} = 4.05 \frac{\text{ft}^3}{\text{sec}}$$

Knowing A and Q, T can be solved for.

$$T = \frac{3.0 \times 9.69 \ldots}{4.05} = 7.182 \ldots \text{ or } 7.2 \text{ hr}$$

It will take 7.2 hr to apply 3.0 inches of water to the field.

19.7 Seasonal Need

Seasonal water demand is the amount of water (in inches) that a crop must have during one growing season for maximum production. The seasonal water demand will vary from season to season and for each crop and region. Table 19.5 contains some typical values for three regions of the United States.

Knowledge of the seasonal water demand for a crop in a given area is useful for determining the contribution of irrigation to the cost of production and the total amount of water that will be needed. When the cost of water is known, usually expressed as dollars per acre-feet, as well as the seasonal demand of the crop, the normal rainfall during the growing season, and the number of acres, it is possible to estimate the total amount of water that will be needed and what it will cost. To determine total seasonal use, the efficiency of the irrigation system also must be considered. Typical efficiency is 60–80%.

Table 19.5 Typical seasonal water demand for some crops (in)

	Western region	Central region	Eastern region
Alfalfa	36.0	36.0	33.0
Corn	23.0	25.0	21.0
Cotton	31.0	20.0	19.0
Grain sorghum	20.0	22.0	21.0
Oranges	33.0	–	–
Hay	31.0	–	36.0
Sugar beets	36.0	29.0	–
Tomatoes	19.0	–	14.0

Source: Planning for an Irrigation System, American Association for Vocational Instructional Materials (AAVIM), Athens, Georgia

Problem How much water (ac-ft/yr) is needed to supply 120 acres of cotton in the central region if the normal rainfall during the growing season is 5.0 inches and the efficiency of the irrigation system is 70%?

Solution Using unit cancellation:

$$\frac{\text{ac-ft}}{\text{yr}} = \frac{120\text{ ac}}{1} \times \frac{1\text{ ft}}{12\text{ in}} \times \frac{20.0\text{ in-}5.0\text{ in}}{1\text{ yr}} \times \frac{1}{0.70}$$

$$= \frac{1800}{8.4} = 214.285\ldots \text{ or } 210\ \frac{\text{ac-ft}}{\text{yr}}$$

Problem What is the total water cost if the price is $25.00 per acre-foot?

Solution Using unit cancellation:

$$\frac{\$}{\text{yr}} = 25.00\ \frac{\$}{\text{ac-ft}} \times 210\ \frac{\text{ac-ft}}{\text{yr}} = 5250 \text{ or } 5200\ \frac{\$}{\text{yr}}$$

19.8 Metric Problems

Determining the net water to apply and store in the root zone is dependent on having the appropriate data for the tables in SI units. They are not provided in this text, but additional problems such as system capacity can be computed in SI units.

Problem Determine the pump capacity that will be required to apply 30.5 mm of water to 50.0 ha when the irrigation interval is 10 days and the pump can operate 20.0 hr per day.

Solution Using unit method:

$$\text{Capacity}\left(\frac{\text{m}^3}{\text{min}}\right) = 30.5\text{ mm} \times \frac{1\text{ m}}{1000\text{ mm}} \times \frac{10{,}000\text{ m}^2}{1\text{ ha}} \times 50\text{ ha} \times \frac{1\text{ day}}{20.0\text{ hr}} \times \frac{1}{10\text{ day}} \times \frac{1\text{ hr}}{60\text{ min}} = 1.27\,\frac{\text{m}^3}{\text{min}}$$

By equation:

$$\text{RSC}\left(\frac{\text{m}^3}{\text{hr}}\right) = \frac{A \times \text{DWA}}{\text{IRP} \times \text{HPD} \times 0.1} = \frac{50.0 \times 30.5}{10 \times 20 \times 0.1} = \frac{305}{20} = 15.25 \text{ or } 76.25\,\frac{\text{m}^3}{\text{hr}}$$

Or

$$= 1.27\,\frac{\text{m}^3}{\text{min}}$$

Problem A producer spends 120 hr. irrigating 35.0 hectares. The pump discharges 5.2 cubic meters per minute. What average depth of water (mm) is applied?

Solution

$$\text{Depth (mm)} = \frac{1000\text{ mm}}{\text{m}} \times \frac{5.2\text{ m}^3}{1\text{ min}} \times \frac{1\text{ ha}}{10{,}000\text{ m}^2} \times \frac{1}{35.0\text{ ha}} \times \frac{60\text{ min}}{1\text{ hr}} \times 120\text{ hr} = \frac{3.744\text{ E7}}{3.5\text{ E5}} = 106.97\ldots \text{ or } 110\text{ mm}$$

Problem What is the largest size of lawn (m^2) that can be irrigated in 6.0 hr if a minimum of 1.3 centimeters of water is applied at each irrigation, the system is 90% efficient, and the water supply delivers 13.0 Liters per minute (L/min)?

Solution

$$\text{Area (m}^2\text{)} = \frac{13.0\text{ L}}{\text{min}} \times \frac{1\text{ m}^3}{1000\text{ L}} \times \frac{60\text{ min}}{1\text{ hr}} \times \frac{1}{1.3\text{ cm}} \times \frac{100\text{ cm}}{1\text{ m}} \times 6.0\text{ hr} = \frac{4.68\text{ E5}}{1.3\text{ E3}} = 360\text{ m}^2$$

Chapter 20
Handling, Moisture Management, and Storage of Biological Products

20.1 Objectives

1. Be able to describe the common methods of handling biological products.
2. Be able to determine the size and horsepower requirements of screw-type conveyors.
3. Be able to determine the size and horsepower requirements of pneumatic conveyors.
4. Be able to determine the amount of water to extract from or add to biological products.
5. Understand the requirements of biological product storage.

20.2 Introduction

The term biological product describes all of the food, feed, and fiber produced by agriculture. These products include everything from fruits and vegetables to grain, hay, and cotton. Although the diversity of agricultural production is too broad to be individually covered in this text, the following sections will discuss some of the principles involved in the handling, drying, and storage of these products.

20.3 Handling

Because of the differences in shape, size, and consistency, each product requires a handling system capable of moving that specific product. The designer of a handling system also must consider product perishability and the desired form of the finished product. A harvester designed to harvest tomatoes for the fresh vegetable market will be different from one designed to harvest tomatoes used for canning or other products. Because of the prevalence of grains across the United States, they will be used to illustrate some of the basic principles of handling biological products.

Grains were one of the first products to be mechanically moved because they are small, flow by gravity, and have a relatively hard outer coat. These characteristics

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H.L. Field, J.M. Long, *Introduction to Agricultural Engineering Technology*,
https://doi.org/10.1007/978-3-319-69679-9_20

allow them to be moved by mechanical devices. Two of these, augers and pneumatic conveyors, will be discussed in the following sections.

20.4 Augers

Augers are available in two types, Archimedean screw and belt. Of the two, the screw-type auger is the most popular in agriculture, and it is the one that will be used in the following discussion and sample problems. An auger has flights, like stretched out threads on a bolt, which turn inside a tube. Another name for an auger is a screw conveyor. As the auger rotates, the flights move the product through the tube similarly to the way that threads move a nut on a bolt. Augers are available in different diameters and are capable of handling many different products. Augers have the advantage of requiring less horsepower per bushel and having fewer mechanical parts than pneumatic systems; but their disadvantages include the danger of the exposed auger at the inlet and damage to the product and their space requirement because they are usually used at a maximum angle of about 45° when moving grain. This places the inlet some distance from the outlet, Fig. 20.1.

Augers are selected on the desired capacity (bu/hr) and length requirements. The length is usually predetermined by the distance needed to move the grain, if horizontal, or by the discharge height and angle of the auger. The selection criteria are primarily based on the auger diameter and speed because the capacity increases as the speed increases. The following discussion will illustrate how the capacity and energy requirements for augers can be determined.

Tables 20.1 and 20.2 contain typical values for two sizes of screw augers and two different crops. This type of information can be used to make decisions in managing a grain handling system, such as determining the size of auger required to convey grain at a given rate (bu/hr).

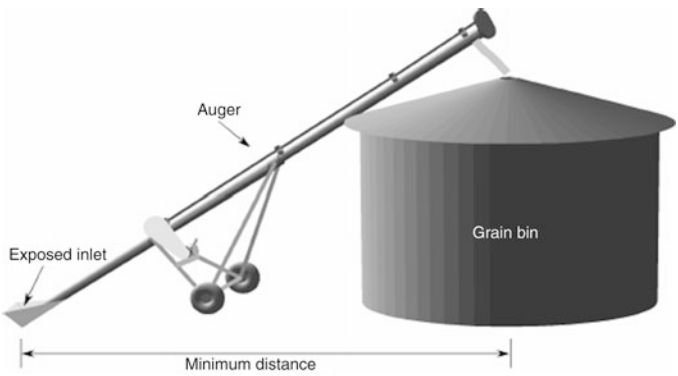

Fig. 20.1 Auger conveyor

Table 20.1 Screw auger capacity handling dry corn (12-inch exposure)

Auger		Auger angle					
		0°		45°		90°	
Size	RPM	bu/hr	hp/10 ft	bu/hr	hp/10 ft	bu/hr	hp/10 ft
4 in	200	150	0.12	120	0.15	60	0.11
	400	290	0.29	220	0.29	130	0.24
	600	420	0.38	310	0.45	190	0.36
6 in	200	590	0.38	500	0.44	280	0.32
	400	1090	0.56	850	0.88	520	0.70
	600	1510	0.84	1160	1.28	740	1.05

Note: For total horsepower, 10% must be added for drive train losses.
Source: *Structures and Environment Handbook, MWPS-1*, Midwest Plan Service, Iowa State University, Ames, Iowa, 1987, Section 534.

Table 20.2 Screw auger capacity handling dry soybeans (12-inch exposure)

Auger		0°		Auger angle			
				45°		90°	
Size	RPM	bu/hr	hp/10 ft	bu/hr	hp/10 ft	bu/hr	hp/10 ft
4 in	200	140	1.00	125	0.17	70	0.12
	400	270	0.21	215	0.35	130	0.26
	600	390	0.34	315	0.51	180	0.40
6 in	200	500	0.40	360	0.57	220	0.40
	400	990	0.84	690	1.20	390	0.79
	600	1350	1.20	930	1.71	500	1.10

Note: For total horsepower, 10% must be added for drive train losses.
Source: *Structures and Environment Handbook, MWPS-1*, Midwest Plan Service, Iowa State University, Ames, Iowa, 1987, Section 534.

Problem What is the minimum size of auger that can be used to convey dry corn at the rate of 500 bushels per hour if the maximum angle is 45°?

Solution Use Table 20.1 and select the correct column and line.
Using Table 20.3, the minimum size of auger is 6 inches.

Table 20.3 Value for problem

Auger		Auger angle					
		0°		45°		90°	
Size	RPM	bu/hr	hp/10 ft	bu/hr	hp/10 ft	bu/hr	hp/10 ft
4 in	200	150	0.12	120	0.15	60	0.11
	400	290	0.29	220	0.29	130	0.24
	600	420	0.38	310	0.45	190	0.36
6 in	200	590	0.38	500	0.44	280	0.32
	400	1090	0.56	850	0.88	520	0.70
	600	1510	0.84	1160	1.28	740	1.05

Another use of Tables 20.1 and 20.2 is to determine the horsepower required to operate the auger.

Problem How much horsepower (including drive train) is required to operate a 100.0 ft, 6.0-inch auger, installed at 45° and conveying 690 bushels of soybeans per hour?

Solution Use Table 20.2 and select the correct column and line.

Table 20.4 Value for problem

Auger		Auger angle					
		0°		45°		90°	
Size	RPM	bu/hr	hp/10 ft	bu/hr	hp/10 ft	bu/hr	hp/10 ft
4 in	200	140	1.00	125	0.17	70	0.12
	400	270	0.21	215	0.35	130	0.26
	600	390	0.34	315	0.51	180	0.40
6 in	200	500	0.40	360	0.57	220	0.40
	400	990	0.84	690	1.20	390	0.79
	600	1350	1.20	930	1.71	500	1.10

Using Table 20.4, the power requirement is 1.20 hp/10 ft. It is important to read the note at the bottom of Table 20.2. Ten percent must be added for drive train losses.

Therefore:

$$\text{hp} = \left(\frac{1.2\,\text{hp}}{10\,\text{ft}} \times 100\,\text{ft}\right) \times 1.10 = 13.2 \text{ or } 13\,\text{hp}$$

The minimum horsepower required by the auger, including the drive train, is 13 hp.

20.5 Pneumatic Conveyors

Pneumatic conveyors are used to move grain and other products using air. Pneumatic conveyors are more flexible than augers because the duct does not need to be in a straight line. They are self-cleaning and do not have an exposed auger at the inlet. They do require more horsepower per bushel and are noisier than augers. Three types of pneumatic conveyors are used: positive pressure, push units, negative pressure, vacuum, and combination of negative and positive pressure. In a positive pressure unit, a blower supplies the pressure, and the product enters the airstream through a rotary air lock. The material is moved through the duct with the air, Fig. 20.2.

In a negative pressure unit, the material is vacuumed up by the inflowing air and then separated from the air in a cyclone separator. The material collects in the bottom of the separator where it can be released with a gate valve or a rotary lock. The air continues to the pump and out through a filter into the atmosphere, Fig. 20.3.

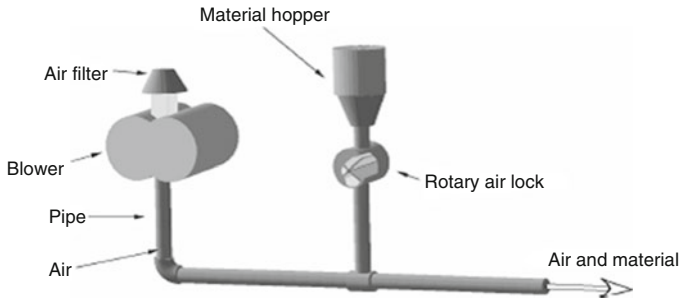

Fig. 20.2 Positive pressure pneumatic system

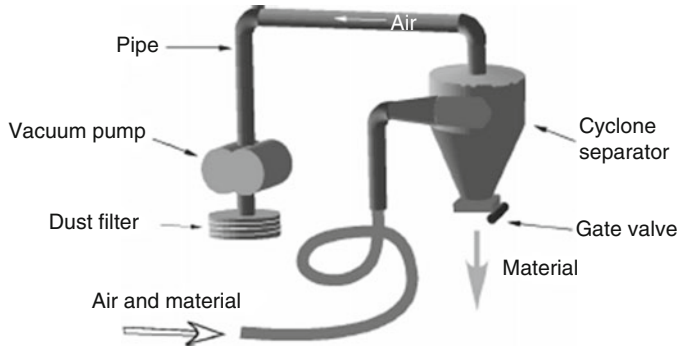

Fig. 20.3 Negative pressure pneumatic system

20.6 Sizing a Pneumatic System

In a combination system, the material is picked up by the inflow of a negative pressure system, and then it passes through a rotary air lock into the positive pressure airstream coming from the pump.

The capacity and the horsepower requirements of pneumatic conveyors depend on eight factors:

1. The horizontal distance that the material is moved
2. The diameter of the pipe
3. The vertical distance that the material is moved
4. The number of bends in the pipe
5. The elevation above sea level
6. The temperature of the outside air
7. The type of material being conveyed
8. The moisture content of the material

To design a pneumatic system that accounted for the effect of these factors would require an experienced engineer.

Table 20.5 is an example of the information available from a manufacturer for sizing pneumatic systems. This information includes six modification factors that

Table 20.5 Pressure system conveyor capacities for dry corn (bu/hr)

Pipe size (in)	Hp	Equivalent length (ft)					
		50	100	200	250	300	350
3	10	450	400	350	320	295	265
4	15	650	575	500	460	420	380
5	25	1100	1000	900	830	755	685
6	40	2100	1950	1800	1650	1510	1370
8	75	4300	3900	3500	3220	2940	2660
10	100	5800	5100	4500	4240	3980	3720
Modifications to capacity							
1. Vertical pipe × 1.20 = equivalent horizontal length							
2. Capacity in wheat = 90% of corn							
3. Capacity in soybeans = 80% of corn							
4. Add 20 ft of equivalent horizontal pipe for each 90° bend in pipe							
5. Reduce capacity by 4.0% for each 1000 ft above sea level							
6. Reduce capacity by 2.0% for each 10° F above 70° F							

Source: Beard Industries, Frankfort, Indiana 46041.

must be considered when determining the capacity of a pneumatic system. The data show that as the horizontal length (ft) of the pipe increases the capacity of the system (bu/hr) decreases. As the pipe diameter increases (in) the capacity increases.

To provide an easy way to estimate the amount of reduction caused by factors 1 and 4, in the table, the equivalent feet of pipe is determined. The equivalent feet of pipe procedure use constants to determine the amount of horizontal pipe that will cause the same reduction in capacity as the factor in question. For example, the first modification to capacity listed in Table 20.5 shows that each foot of vertical pipe causes the same reduction in capacity as 1.20 ft of horizontal pipe. Thus, the equivalent feet for a vertical section of pipe is determined by multiplying the vertical length (ft) by 1.2. Expressed as an equation:

$$\text{TEF} = (F_{\text{H}} + F_{\text{B}} + F_{\text{V}})$$

where TEF = total equivalent feet; F_{H} = horizontal distance, ft; F_{B} = equivalent feet for bends; F_{VU} = equivalent feet for vertical up sections.

Adjustments for factors 2, 3, 5 & 6 in Table 20.5 are handled differently. The capacity of the system is adjusted for the effect of factors 5, 6, and 7 by reducing the capacity by the appropriate percentage.

Problem What is the capacity of the system in Fig. 20.4 if the material to be moved is dry soybeans?

Solution The first step is to determine the total equivalent feet for the pipe for factors 1 and 4. Note: The last section of pipe does not have a length dimension because the assumption is used that the force of gravity exceeds the resistance of the pipe. Therefore, vertical down sections of pipe are not included.

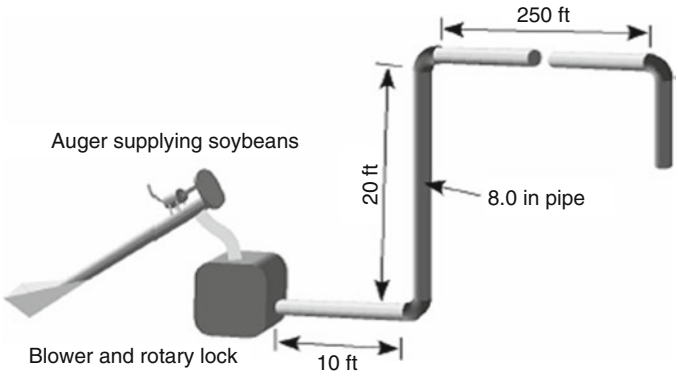

Fig. 20.4 Pressurized conveyor for sample problem

$$\begin{aligned}\text{TEF} &= (F_{\text{H}} + F_{\text{B}} + F_{\text{V}}) \\ &= \left((250\,\text{ft} + 10\,\text{ft}) + \left(3\,\text{bends} \times \frac{20\,\text{ft}}{\text{bend}}\right) + (20\,\text{ft} \times 1.2)\right) = 344\,\text{ft}\end{aligned}$$

Although the actual length of pipe in Fig. 20.4 is 280 ft, because of the bends and the vertical up sections, the equivalent distance is 344 ft.

The next step is to use Table 20.5 to determine the capacity of an 8.0-inch duct with an equivalent distance of 344 ft. The closest value is 2660 bu/hr. Note that Table 20.5 gives values for corn. Because the capacity of a pressurized system for soybeans is 80% of the capacity for corn (modification 3), the system capacity in Fig. 20.4 is:

$$\frac{\text{bu}}{\text{hr}} = 2660\,\frac{\text{bu}}{\text{hr}} \times 0.80 = 2100\,\frac{\text{bu}}{\text{hr}}$$

The pneumatic system in Fig. 20.4 is 2,100 bushels per hour.

Information to determine the capacities of auger, pneumatic, and bucket conveyor systems for other crops and situations are available from manufacturers and agricultural extension personnel.

20.7 Moisture Management

Water and its addition to or removal from agricultural products is an extremely important topic. The moisture contents of grain, feed, hay, crops, meat, and dairy products are but a few examples of agricultural products where moisture must be carefully managed. Moisture may be added to or removed from products depending upon the desired final condition. Moisture is removed from products by drying. Drying usually is done to change the consistency or to extend the storage life of the product. For example, fruits and meats may be dried to change the way that they are handled, stored, and eaten. Grains and forages are dried to extend their storage life.

Some agricultural products, such as grains and forages, will dry naturally to equilibrium moisture content (the same as that of the environment) if left in the field. But with these and other products, good management sometimes dictates that the crop be harvested at a wetter stage and dried artificially. Artificial drying is accomplished by causing natural or heated air to flow around and/or through the product. Artificially heated air is often used, because heating reduces the relative humidity of the air, increasing the amount of moisture each pound of air can absorb.

The management of a drying system requires the ability to be able to predict the amount of moisture that must be removed from the product. For other products, it is important to be able to predict the amount of water that must be added. The following discussion presents a method for determining the amount of moisture that must be added to or removed from biological products.

The moisture content of a given material is stated as a percent using either the wet-weight or the dry-weight basis. The difference between the wet-weight basis and the dry-weight basis is the value used in the denominator of the ratio. The wet-weight basis uses the weight of the product as it is received; the dry-weight basis uses the oven-dry weight (dry matter) of the product.

Study Fig. 20.5. The total weight of the product is 4 pounds. When the amount of water is expressed on the dry-weight basis, the percentage is:

$$\frac{1\,\text{lb water}}{3\,\text{lb dry matter}} \times 100 = 33\%$$

Expressed on the wet-weight basis, the amount of water is:

$$\frac{1\,\text{lb water}}{4\,\text{lb total}} \times 100 = 25\%$$

These relationships are explained in the following equations:Dry-weight basis:

$$\%\ \text{MDB} = \left(\frac{\text{WW} - \text{DW}}{\text{DW}}\right) \times 100$$

Wet-weight basis:

$$\%\ \text{MWB} = \left(\frac{\text{WW} - \text{DW}}{\text{DW}}\right) \times 100$$

where % MDB = percent moisture, dry-weight basis; % MWB = percent moisture, wet-weight basis; WW = wet weight or weight of product before drying; DW = oven-dry weight, or weight of product after drying; WW − DW = weight of moisture removed.

It is impractical and often undesirable to remove all of the moisture from grain as well as many other products. Grain usually is considered to be dry when the moisture content is sufficiently low to discourage enzymatic action, insects and

Fig. 20.5 Dry-weight, wet-weight basis illustration

mold growth. This is usually about 12% moisture content, %MWB, depending upon the grain. Standards have been established to determine the heating time and temperature required to obtain an official oven-dry sample of grain.

Either moisture content basis may be used with agricultural products; so to avoid confusion or misunderstanding, the basis being used should always be specified. This can be accomplished by writing the numerical value of the moisture content followed by %MDB or %MWB.

Problem Express the moisture content on the wet-weight basis and the dry-weight basis for a product that weighs 150.0 pounds when wet, and 80.0 pounds when dry.

Solution Wet-weight basis:

$$\%\ \text{MWB} = \left(\frac{\text{WW} - \text{DW}}{\text{WW}}\right) \times 100 = \left(\frac{150\,\text{lb} - 80.0\,\text{lb}}{150\,\text{lb}}\right) \times 100$$
$$= 46.666\ldots \text{or} 46.7\%$$

On the wet-weight basis, the product is 46.7% moisture.

Dry weight basis:

$$\%\ \text{MDB} = \left(\frac{\text{WW} - \text{DW}}{\text{WW}}\right) \times 100 = \left(\frac{150.0\,\text{lb} - 80.0\,\text{lb}}{80.0\,\text{lb}}\right) \times 100 = 87.5\%$$

On the dry-weight basis, the product is 87.5% moisture.

Notice that the only difference in the values used in the two equations is in the denominator of the ratio. For the DW basis, the dry weight is used, and for the WW basis, the wet weight is used.

One aspect of the DW basis is that the percentage of moisture can be greater than 100%. For example, if a product has a wet weight of 100 ounces and a dry weight of 40 ounces, the MWB is 60%, and the MDB is 150%. This is why the standard moisture of many products is given on the wet-weight basis.

20.8 Adding or Removing Water

During the life of many products, it may be necessary to remove or to add water. Grain must be dried for storage, and the same grain may have to be tempered (have water added) for processing. Water may be added to or removed from products such as catsup to produce the desired consistency and so on. The dry-weight and wet-weight basis equations also can be used to determine the amount of water to put into or take out of any biological product.

The calculations for determining how much water to add or remove require three steps, and they must be completed in the correct sequence:

1. Determine the dry weight of the material at its original state. The weight of the dry material does not change as the moisture content changes; moisture may be added or removed, but the amount of dry matter or the dry weight remains the same.
2. Using the dry weight that was determined in step 1, solve for the new wet weight (the weight of the material at the new moisture content).
3. The amount of moisture to add or to remove is the difference between the weight of the product in the original state and the new wet weight.

To solve for the dry weight or the wet weight, the wet-weight basis and dry-weight basis equations are rearranged. The first two equations are used when the moisture is on the dry-weight bases, and the second two equations are used when the moisture is on the wet-weight basis.

Dry-weight basis:

$$\text{DW} = \frac{\text{WW}}{\left(1 + \dfrac{\%\text{MDB}_\text{I}}{100}\right)}$$

$$\text{WW}_\text{n} = \text{DW} \times \left(1 + \frac{\%\text{MDB}_\text{E}}{100}\right)$$

Wet-weight basis:

$$\mathrm{DW} = \mathrm{WW} \times \left(1 - \frac{\%\,\mathrm{MWB_I}}{100}\right)$$

$$\mathrm{WW_n} = \frac{\mathrm{DW}}{\left(1 - \frac{\%\,\mathrm{MWB_E}}{100}\right)}$$

The subscripts n = new, e = ending, and I = initial

The following problems illustrate the uses of these equations.

Problem How much water needs to be removed (lb) to dry 1000.0 pounds of product at 70.0% MWB to 20.0% MWB?

Solution Follow the three-step process:

Step one: Because the moisture has been measured by the wet-weight basis, the second of the two equations must be used. Start by solving for the dry weight of the product:

$$\mathrm{DW} = \mathrm{WW} \times \left(1 - \frac{\%\,\mathrm{MWB_I}}{100}\right) = 1000 \times \left(1 - \frac{70.0\%}{100}\right)$$

$$= 1000.0 \times 0.30 = 300\,\mathrm{lb}$$

Step two: Solve for the new wet-weight at the desired moisture content:

$$\mathrm{WW_n} = \frac{\mathrm{DW}}{1 - \frac{\%\,\mathrm{MWB_E}}{100}} = \frac{300\,\mathrm{lb}}{1 - \frac{20\%}{100}} = 375\,\mathrm{lb}$$

Step three: The amount of water that needs to be removed is the difference between the initial wet weight ($\mathrm{WW_I}$) and the new wet weight ($\mathrm{WW_E}$). Thus, the amount of water (lb) that must be removed is:

$$\mathrm{lb\,water} = \mathrm{WW_I} - \mathrm{WW_n} = 1000\,\mathrm{lb} - 375\,\mathrm{lb} = 625\,\mathrm{lb}$$

To change the product from the original 70% MWB to 20% MWB, 625 pounds of water must be removed.

Problem A miller needs to raise the moisture content of 1000 bushels of wheat from the storage condition of 9.0% MDB to 16.0% MDB. How much water (lb) needs to be added?

Solution Step one: Use the dry-weight equations and the conversion value of 1 bu = 60 lb. to solve for the pounds of dry matter:

$$\mathrm{DW(lb)} = \frac{\mathrm{WW}}{1 + \frac{\%\,\mathrm{MDB}}{100}} = \frac{1000\,\mathrm{bu} \times \frac{60\,\mathrm{lb}}{\mathrm{bu}}}{1 + \frac{9.0\%}{100}} = \frac{60{,}000\,\mathrm{lb}}{1.09} = 55{,}045.871..\mathrm{lb}$$

Step two: Determine the weight of the product at the new wet weight:

$$\mathrm{WW_n} = \mathrm{DW} \times \left(1 + \frac{\%\mathrm{MDB}}{100}\right)$$
$$= 55{,}045.87156\ \mathrm{lb} \times \left(1 + \frac{16.0\%}{100}\right) = 63{,}853.212..\mathrm{lb}$$

Step three: Determine the water to add. Because this problem is an example of adding water, the initial weight is subtracted from the new wet weight:

$$\mathrm{lb\,water} = \mathrm{WW_n} - \mathrm{WW_i} = 63{,}853.212101\ \mathrm{lb} - 60{,}000\ \mathrm{lb} = 3853.212..$$

or $3800\,\mathrm{lb\,water}$

The miller should add 3800 pounds of water to the wheat to bring it up to 16% MDB.

On occasion, it is useful to know how to convert from one moisture basis to the other. This can be accomplished with the following equations:

$$\%\ \mathrm{MDB} = \frac{100 \times \%\ \mathrm{MWB}}{100 - \%\ \mathrm{MWB}}$$
$$\%\ \mathrm{MWB} = \frac{100 \times \%\ \mathrm{MDB}}{100 + \%\ \mathrm{MDB}}$$

Problem Determine the percent moisture, dry basis (%MDB), of a product if the percent moisture, wet basis (%MWB), is 50%.

Solution

$$\%\ \mathrm{MDB} = \frac{100 \times \%\mathrm{MWB}}{100 - \%\mathrm{MWB}} = \frac{100 \times 50\%}{100 - 50\%} = \frac{5000}{50} = 100\%$$

Problem Determine the percent moisture, wet basis (%MWB), of a product that is 23.25% moisture, dry basis (MDB).

Solution

$$\%\ \mathrm{MWB} = \frac{100 \times \%\mathrm{MDB}}{100 + \%\mathrm{MDB}} = \frac{100 \times 23.25}{100 + 23.25} = 18.864\ldots\,\mathrm{or}\,18.86\%$$

20.9 Storage of Biological Products

The term biological product has been used throughout this chapter because products such as grains, fruits, and vegetables are living organisms. Because they are alive, they have minimum requirements for moisture, temperature, and air to maintain their viability. The life of the product can be extended if the temperature, moisture, or air is modified during storage. The challenge for managers of many such products is to extend the storage life of the product without damaging its viability, color, taste, or texture. Recommendations for optimum environments for the

storage of biological products can be obtained from the extension service or any department of agricultural engineering.

20.10 Metric Problems

The auger and pneumatic capacity problems are worked the same. The only difference is using the appropriate values in SI units.

Adding and removing of water from products use the same equations; the difference is using units of mass instead of weight.

Problem How much water (kg) must be removed from 1.2 metric tons (t) of grain to lower the moisture from 14.5%DB to 11.0%DB?

Solution Follow the three steps:

Step one: Determine the dry mass:

$$\begin{aligned}\text{DW (kg)} &= \frac{\text{WW}_\text{I}}{\left(1+\dfrac{\%\ \text{MDB}_\text{I}}{100}\right)} = \frac{1.2\,\text{t}}{1+\dfrac{14.5}{100}} \times \frac{1000\,\text{kg}}{\text{t}} = \frac{1200}{1.145} \\ &= 1048.03\ldots\,\text{kg}\end{aligned}$$

Step two: New wet mass:

$$\begin{aligned}\text{WW}_\text{n} &= \text{DW} \times \left(1+\frac{\%\ \text{MDB}_\text{E}}{100}\right) = 1048.03\,\text{L} \times \left(1+\frac{11.0}{100}\right) \\ &= 1163.31\ldots\,\text{kg}\end{aligned}$$

Step three: Subtract original and new wet mass:

$$\begin{aligned}\text{Water(kg)} &= \text{WW}_\text{I} - \text{WW}_\text{E} = \left(1.2\,\text{t} \times \frac{1000\,\text{kg}}{\text{t}}\right) - 1163.31\ldots \\ &= 36.68\ldots\,\text{or}\,36.7\,\text{kg}\end{aligned}$$

Chapter 21
Animal Waste Management

21.1 Objectives

1. Understand the importance of animal waste management.
2. Be able to describe the methods of handling solid animal waste.
3. Be able to determine the maximum amount of solid animal waste that can be applied to the soil.
4. Be able to describe the methods of handling liquid animal waste.
5. Be able to determine the capacity of storage units for animal waste.
6. Be able to describe animal waste treatment methods.

21.2 Introduction

When animals are free ranging, "dilution is the solution to pollution." Animals that range freely tend to distribute their waste over a large area, and natural processes disseminate the waste. When animals are confined, waste is concentrated in one spot, and it becomes part of the management of the animals. Animal waste management is no longer an option in a livestock business; it is a requirement. A plan for the collection and disposal of animal waste must be part of any livestock facility plan. Failure to provide adequate waste management collection and storage facilities and disposal equipment can lead to pollution problems with legal complications, animal health problems, increased production costs, and generally undesirable working conditions. In most states, confinement operations must have a comprehensive nutrient management plan. There are three aspects of animal waste management:

1. Waste handling
2. Waste treatment
3. Waste disposal

When the decision is made during the planning process, a producer can choose from a variety of waste handling, treatment, and disposal systems to manage animal waste. Selecting a system after a facility has been built limits the options.

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21.3 Handling Solid Animal Waste

Waste containing 20% or more solids or with a moisture content of 50% MWB or less is considered to be solid waste. Proper handling of solid waste inside buildings requires solid floors that can be bedded or drained. The waste is collected and usually is not treated except by the natural processes that occur while it is stored. The preferred method for disposal is mimicking the natural system—spread it on the land. If not done correctly, disposal of solid animal waste on the land can reduce plant production, produce offensive odors, and contribute to the contamination of ground and surface water. The NRCS[1] has developed standards for the application of solid animal waste on land. These standards are based on soil type, slope, and distance from surface and groundwater. The general standards are:

1. No application to frozen or snow-covered soil when slope is greater than 5% unless special provisions are made to control runoff.
2. No application to cropland that exceeds soil loss tolerances.
3. No application on any cropland with slopes greater than 15%.
4. No application within 200 feet of wells, sinkholes, or surface water.
5. Liquid cannot be applied to soils with less than 10 inches of at least moderately permeable soil.
6. No application on organic soils with seasonal water table within 1 foot of the surface.
7. No application on floodplains where flooding occurs more frequent than once in 10 years.
8. Application can occur on floodplains if the injection or immediate incorporation method is used.
9. No intentional application on established waterway or any area where there may be concentrated water flow.
10. No more than 25% of the surface may be covered.

Failure to follow these standards can cause contamination of the ground or surface water and the possibility of fines or litigation.

Note: Different computer programs are available to help producers calculate the amount of livestock waste that can be applied to a field or pasture. The manual process explained in the following sections shows the steps and types of information required for any of the computer programs.

For accurate results, the first step in determining the amount of solid animal waste that can be applied to the soil is to analyze both the solid waste and the soil for the amounts of nitrogen and phosphorous they contain. If the waste has not been tested, Appendix VI may be used to estimate the nutritional content. These values are estimates because the animal's ration, the type and quantity of bedding used, the amount of liquid added, the type of housing and manure handling system, and the storage system all affect the nutrient content of the animal waste.

[1] *Waste Utilization, Code 633*, Natural Resources Conservation Service, 2002

When the nutritional content of the soil is unknown, it must be estimated before Appendixes VI (Solid Animal Waste Production and Characteristics), VII (Nutrient Utilized by Crops), and VIII (Maximum Annual Application Rates for Phosphates Based on Soil Family) can be used to determine the amount of waste that may be applied.

The primary governing principle for the application of solid animal waste is that no more nutrients can be applied to the soil than what will be removed from the field in crops or animal weight. It is unlikely that the amount of each nutrient in the waste can be matched with the needs of the plants; so the nutrient with the most restrictive amount determines the maximum amount of waste that can be applied.

Note: This method assumes that more than one application per year will be used to distribute the total amount of waste.

The steps in calculating the amount of waste that can be applied are:

1. Determine the amount of nutrients produced per day, Appendix VI.
2. Calculate the pounds of nutrients per pound of waste.
3. Determine the amount of nutrients used for the expected crop, Appendix VII.
4. Determine the maximum amount of phosphorous for the soil type, Appendix VIII.
5. Calculate the pounds of waste that can be applied.

Problem Determine the amount of solid waste from 1000 lb. dairy cows that can be applied to a coarse loamy soil with a pH of 6.5 that will be used to raise 60 bushels per acre of wheat. Note: In this example, we will assume that there are no nutrients in the soil.

Solution In this type of a problem, a table is useful for determining the answer, for example, Table 21.1. First, determine the amount of nutrients in the waste and the maximum amounts of phosphorous and nitrogen that can be applied. This is accomplished by selecting the correct values from Appendixes VI, VII, and VIII and converting them to pounds of nutrient per pound of waste. From Appendix VI, the nutrients produced per day are:

$$\text{Nitrogen (N)} = 0.14\,\frac{\text{lb}}{\text{day}}$$

$$\text{Phosphorous (P)} = 0.27\,\frac{\text{lb}}{\text{day}}$$

Each cow produces 82 lb. of waste per day, Appendix VI. The pounds of nutrient per pound of waste can be calculated using unit cancellation:

$$\frac{\text{lb of nitrogen}}{\text{lb of waste}} = \frac{0.14\,\text{lb N}}{1\,\text{day}} \times \frac{1\,\text{day}}{82\,\text{lb waste}} = 1.7\text{E}-3\,\frac{\text{lb N}}{\text{lb waste}}$$

$$\frac{\text{lb of Phosphorus}}{\text{lb of waste}} = \frac{0.27\,\text{lb P}}{1\,\text{day}} \times \frac{1\,\text{day}}{82\,\text{lb waste}} = 3.3\,\text{E}-3\,\frac{\text{lb P}}{\text{lb waste}}$$

The next step is to use Appendix VII to determine the nutrients used by the crop:

Table 21.1 Solution to problem

Nutrient	Soil limits (lb/ac)	Net nutrients used by crop (lb/ac)	Pounds of nutrient per pound of waste (lb/lb)	Application rate of waste (lb/ac/yr)
Nitrogen	–	125	1.7×10^{-3}	7400*
Phosphorous	–	50	3.3×10^{-3}	15,000
Phosphorous	400	–	3.3×10^{-3}	120,000

$$*\text{Application rate} = \frac{125\,\text{lb N}}{1\,\text{ac}} \times \frac{1\,\text{lb waste}}{1.7\text{E}-3\,\text{lb N}} = 73{,}529.41\,\text{or}\,7400\,\text{lb}$$

$$**\text{Application rate} = \frac{50\,\text{lb of P}}{1\,\text{ac}} \times \frac{1\,\text{lb waste}}{3.3\,\text{E}-3\,\text{lb P}} = 15{,}151.51\ldots\,\text{or}\,15{,}000\,\text{lb}$$

$$**\text{Application rate} = \frac{400\,\text{lb P}}{1\,\text{ac}} \times \frac{1\,\text{lb waste}}{3.3\,\text{E}-3\,\text{lb P}} = 121{,}212.12\ldots\,\text{or}\,120{,}000\,\text{lb}$$

$$\text{Nitrogen} = 125\,\text{lb/ac}$$
$$\text{Phosphorous} = 50\,\text{lb/ac}$$

The last information needed to find the solution is the maximum amount of phosphorous that can be applied to the soil based on soil type. Consult Appendix VIII for this information:

$$\text{Phosphorous} = 400\ \text{lb/ac}$$

The solution is found by calculating the application rate (lb/ac/yr) of waste for each nutrient. The maximum amount of waste that can be applied is determined by the smallest of three values: the nitrogen used by the plant, the phosphorous used by the plant, and the phosphorous that can be applied to the soil.

Table 21.1 shows that nitrogen is the most restricted nutrient (7400 lb/ac/y). Therefore, the maximum amount of waste from the dairy cows that can be annually applied is 7400 lb per acre per year.

In the previous sample problem, the nutrients available in the soil were not considered. The actual amount of waste than can be applied is the difference between the nutrients used by the crop and the amount of nutrients already available in the soil.

Another aspect of solid waste management is determining how many acres are required to dispose of the waste being produced.

Problem How many acres will be required to distribute all of the waste from a 50-cow dairy? Use the cows in the previous problem.

Solution The answer to this question can be found by using the 7400 lb of waste per acre per year from the previous problem, additional information from Appendix VI

and unit cancellation. Appendix VI shows that each 1000 lb dairy cow produces 82.0 lb of waste per day. Then:

$$\begin{aligned} \text{ac} &= \frac{1\,\text{ac}}{7400\,\text{lb waste}} \times \frac{82.0\,\text{lb waste}}{\text{cow-day}} \times 50\,\text{cows} \times 365\,\text{days} \\ &= \frac{1{,}496{,}500}{7400} \\ &= 202.22\ldots \text{or } 202\,\text{ac} \end{aligned}$$

For the 50-cow dairy herd, a minimum of 202 acres are required to dispose of the animal waste each year. It is important to remember that in the original problem we assumed that the soil contained no nitrogen or phosphorous. Any nitrogen or phosphorous in the soil reduces the amount of waste that may be applied and increases the number of acres required.

21.4 Handling Liquid Waste

Handling of liquid or slurry waste from buildings involves scraping or flushing the waste from where it is dropped by the animal into a pit or a storage tank. Once collected, the waste is treated and/or disposed. Open feedlot waste is handled as runoff-carried waste, with natural precipitation carrying the liquid or the slurry, flowing from the pens into a drainage and collection system for subsequent removal or treatment and disposal. Liquid waste usually is handled by pumping and is disposed of by being spread on the surface of or injected into the soil. The maximum amount of waste that can be spread in liquid form is determined using the same procedure as that used for solid waste.

Liquid waste is more difficult to manage than the solid because it must be stored in tanks or pits and must be pumped. In addition, because animal waste should not be spread on frozen ground, the storage system must have the capacity to store all of the waste while the ground is frozen.

Problem What size of above ground tank (gal) is required to store all of the waste from a 100-sow farrowing barn if the pigs are with the sows and the waste must be stored for 6 weeks?

Solution Using Appendix VI and unit cancellation (Note: Weights can be converted to volumes if the density is known):

$$\begin{aligned} \text{gal} &= \frac{1\,\text{gal}}{0.13368\,\text{ft}^3} \times \frac{1\,\text{ft}^3}{60.0\,\text{lb}} \times \frac{33.0\,\text{lb}}{\text{day-sow}} \times \frac{7.0\,\text{day}}{1\,\text{week}} \times \frac{6\,\text{weeks}}{1} \times \frac{100\,\text{sows}}{1} \\ &= \frac{138{,}600}{8.0208} \\ &= 17{,}280.07\ldots \text{or } 17{,}300\,\text{gal} \end{aligned}$$

An additional problem that arises using liquid waste is the space required for the storage tank.

Problem Determine the height of the tank in the previous problem if the space available for the tank limited to 20.0 ft in diameter?

Solution This is a good problem to use the unit method:

$$\begin{aligned} \text{ft} &= \frac{0.13368\,\text{ft}^3}{\text{gal}} \times \frac{17{,}300\,\text{gal}}{1} \times \frac{1}{\pi \text{ x } (20.0\text{ft})^2/_4} \\ &= \frac{2312.664}{314.159\ldots} \\ &= 7.3614\ldots \text{ or } 7.36\text{ft}. \end{aligned}$$

21.5 Waste Treatment

Waste treatment is an operation performed on waste that makes it more amenable to ultimate disposal. Two basic methods of biological treatment are used: aerobic and anaerobic.

21.5.1 Aerobic Treatment

Aerobic treatment occurs when the environment has sufficient dissolved oxygen available in the waste to allow aerobic bacteria (oxygen-using) to break down the organic matter in the waste. It is essentially an odorless process. Three methods of treatment that use aerobic bacteria are composting, aerobic lagoons, and spray runoff.

Composting is accomplished by piling the waste and turning it frequently to provide aeration for aerobic bacterial decomposition while maintaining a high-enough temperature in the pile to destroy pathogenic organisms and weed seeds. The volume of composted waste may be reduced to between by 40–70% of the original waste volume.

An aerobic lagoon is a relatively shallow basin (3–5 ft deep) into which the liquid waste is added. The decomposition of the organic matter is accomplished by aerobic bacteria. Agitating the surface or blowing air into the liquid provides oxygen for the bacteria and accelerates the process.

In the spray-runoff treatment, an area is leveled and sloped so that water flows evenly and then is planted to grass. The bacteria that live on the wet surface of the grass and soil accomplish the waste decomposition.

21.5.2 Anaerobic Treatment

Anaerobic treatment is accomplished by anaerobic bacteria that consume the oxygen in the organic matter itself as the organic matter decomposes. In this process, odorous gases are produced. The most common method using this treatment is the anaerobic lagoon.

The anaerobic lagoon is a relatively deep (12–14 ft) basin that contains liquid waste and provides a climate for decomposition by anaerobic bacteria. Thus, no attempt is made to introduce oxygen into the liquid. The anaerobic lagoon is able to decompose more organic matter per unit of volume than the aerobic lagoon. However, the odor it produces may determine where it can be located.

21.6 Metric Problems

The principles of animal waste handling treatment and disposal are the same in SI units. The only differences in the problems are the units that are used.

Problem Determine the amount of solid waste from 91 kg finishing pigs that can be applied to a coarse loamy soil with a pH of 6.5 that will be used to raise 5.0 cubic meters per hectare of wheat. A soil test reveals 35.3 kg of nitrogen and 15.0 kg of phosphorus per hectare available for the plants.

Solution The first step is to use Appendix VI to determine the amount of nitrogen and phosphorus produced by the animals. Note: SI values in Appendix VI are direct conversions.

$$\text{Nitrogen} = 0.0305\,\text{kg/day}$$
$$\text{Phosphorus} = 0.0204\,\text{kg/day}$$

The next step is to determine the kilograms of nutrients per kilograms of waste:

$$\frac{\text{kg of nitrogen}}{\text{kg of waste}} = \frac{0.0305\ \text{kg}_\text{n}}{1\,\text{day}} \times \frac{1\,\text{day}}{5.9\ \text{kg}_\text{w}} = 0.005169\ldots \text{or } 0.0052\frac{\text{kg of nitrogen}}{\text{kg of waste}}$$

$$\frac{\text{kg of phosphorous}}{\text{kg of weight}} = \frac{0.0204\ \text{kg}_\text{p}}{1\,\text{day}} \times \frac{1\,\text{day}}{5.9\ \text{kg}_\text{w}} = 0.003457\ldots \text{or } 0.0034\frac{\text{kg of phosphorous}}{\text{kg of waste}}$$

The next step is to determine the net amount of nutrients needed by the crop. This is determined by subtracting the nutrients available in the soil from the nutrients used by the crop, Appendix VII:

$$\frac{\text{kg N}}{\text{ha}} = \frac{140\,\text{kg N}}{\text{ha}} - \frac{35.3\ \text{kg N}}{\text{ha}} = 104.7\frac{\text{kg N}}{\text{ha}}$$
$$\frac{\text{kg P}}{\text{ha}} = \frac{56\ \text{kg P}}{\text{ha}} - \frac{15\ \text{kg P}}{\text{ha}} = 40\frac{\text{kg P}}{\text{ha}}$$

The last step is to determine the kilograms of waste that can be applied per hectare. This is determined by multiplying the net nutrients used by the crop by the kilograms of nutrients per kilogram of waste:

$$\text{Nitrogen waste}: \frac{\text{kg waste}}{\text{ha}} = \frac{1\,\text{kg waste}}{0.0052\,\text{kg N}} \times \frac{104.7\,\text{kg N}}{\text{ha}} = 20{,}134.61\ldots \text{or } 20{,}000\frac{\text{kg waste}}{\text{ha}}$$

$$\text{Phosphorus waste}: \frac{\text{kg waste}}{\text{ha}} = \frac{1\,\text{kg waste}}{0.0034\,\text{kg P}} \times \frac{40\,\text{kg P}}{\text{ha}} = 11{,}764.7\ldots \text{or } 12{,}000\frac{\text{kg waste}}{\text{ha}}$$

$$\text{Phosphorus soil limits}: \frac{\text{kg waste}}{\text{ha}} = \frac{1\,\text{kg}}{0.0034\,\text{kg P}} \times \frac{448\,\text{kg P}}{\text{ha}} = 131{,}764.7\ldots \text{or } 130{,}000\frac{\text{kg waste}}{\text{ha}}$$

The least amount (kg/ha) is 12,000 for the phosphorus in the waste. This sets the limits of 12,000 kg of waste per hectare per year that can be applied.

Chapter 22
Insulation and Heat Flow

22.1 Objectives

1. Understand the principles of insulation and heat flow.
2. Understand the function of insulation.
3. Understand *R*-values and *U*-values.
4. Be able to calculate the total thermal resistance of a building component.
5. Be able to determine the amount of heat flowing through a building component.

22.2 Introduction

All living organisms have a preferred environment. If the environment is not within the preferred parameters, the organism is stressed. Stress reduces productivity, increases the incidents of illness, shortens the storage life of products, and causes many other problems. In the natural environment, organism can modify their environment by changing location. Once animals and other organisms are confined, they cannot roam; therefore, the environment must be modified to meet their needs. Heating and cooling are two of the ways in which environments are modified.

Heat is a form of energy. It is transmitted in three different ways:

1. Radiation—the exchange of thermal energy, heat, between objects by electromagnetic waves
2. Convection—the transfer of heat by movement of a fluid
3. Conduction—the exchange of heat between contacting bodies that are at different temperatures

The movement of heat by radiation and convection is more difficult to calculate than conduction and will not be discussed in this text. Conduct heat losses will be explained in more detail to illustrate the factors that influence the amount and rate of heat movement.

The amount of and rate of conductive heat movement is controlled by the area through which the heat passes, the difference in temperatures, and the thermal

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resistance of the materials. These concepts and others will be discussed in this chapter. Latter sections will show that the greater the area, the greater the heat flow. A similar relationship exists for temperature. The greater the temperature difference, the greater the heat flow. The thermal resistance of materials is primarily dependent on the density of the material. A material with many small, trapped air spaces will have higher thermal resistance compared to a dense material. A material with high thermal resistance is called insulation.

22.3 Insulation

Insulation is any material that reduces the rate of heat transfer by conduction. All building materials have some resistance to the movement of heat, but some are more resistant than others. A common characteristic of insulation materials is low density (pounds/cubic foot, kilogram/cubic meter). Expanded polystyrene, which has a low density, has a higher thermal resistance than concrete, which has a very high density. Also, as the density of a material increases, for example, by compressing the material or adding water, the thermal resistance is reduced.

Some materials, such as wood, concrete, and certain insulation materials, are considered to be homogeneous; they have a uniform consistency. For these materials, the insulating values are listed as per inch of thickness, Appendix IX. Other materials such as concrete blocks and insulation backed siding are not homogeneous. They may have voids or they may be composed of more than one type of material. The insulating value of these materials is based on a thermal test of a sample, Appendix IX, and a different value must be used for each thickness.

There are three common reasons for insulating houses and other structures (Figs. 22.1 and 22.2).

(1) Insulation reduces loss of heat inside any type of enclosure during the winter months, reducing the amount of supplemental heat required to maintain the temperature of the enclosure; (2) insulation helps reduce heat gain during the summer months, reducing the load on cooling equipment (Fig. 22.1); and (3) insulation is used to manage the condensation point to ensure it does not occur within the wall or

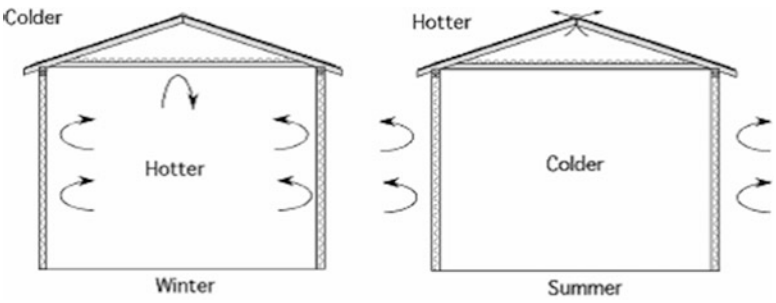

Fig. 22.1 Advantages of insulation for reduction of the loss of heat in the winter or grain of heat in the summer

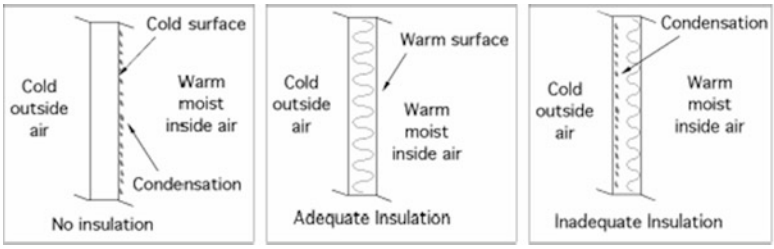

Fig. 22.2 Adequate insulation prevents moisture condensation during the winter

on the inside surface (Fig. 22.2). Condensation is the transformation of water vapor to a liquid. This occurs when warm moist air is cooled below the condensation temperature or comes in contact with a cooler surface. Condensation is explained in more detail in the next chapter on psychrometrics. Condensation may occur on the outside surface of a wall, Fig. 22.2, or on any surface inside the wall if no vapor barrier is used and the insulation is inadequate for the temperature difference. Condensation within a wall reduces the effectiveness of the insulation and promotes mold growth.

22.4 *R*-Values and *U*-Values

Two different numbers are used to describe the insulating properties of materials: *R*-values and *U*-values. The *R*-value is a number that represents the thermal resistance of a material. The *U*-value is a measurement of the thermal conductivity of a material. In the customary units, a *U*-value of 1 means that 1 BTU/h of heat will flow per square foot of area per degree difference in temperature on each side of the material. The term BTU stands for British thermal unit and is the amount of heat required to raise the temperature of 1 pound of water 1 degree Fahrenheit. In the SI unit system, the preferred unit for heat is kilojoules. A joule is equal to 9.478 E − 4 BTU. A BTU is the amount of heat required to raise the temperature of 1 pound of water by 1 degree Fahrenheit.

R-values are the inverse of the *U*-value ($R = 1/\mathrm{U}$). Therefore, the insulating ability of a material increases as the *R*-value increases and as the *U*-value decreases. The *R*-value of a nonhomogeneous building component is the sum of the *R*-values of the materials that make up the component. The nonhomogeneous material may be a construction component such as a concrete block or a part of the building such as a wall or ceiling. The units for U are $\frac{\mathrm{BTU}}{^{\circ}\mathrm{F}\times A_u\times \mathrm{h}}$ or $\frac{\mathrm{J}}{^{\circ}\mathrm{C}\times A_u\times \mathrm{h}}$ where A_u is the unit area of the material through which the heat passes (generally in ft^2 or m^2). Since the units of *R* are the inverse of the units of *U*, the units of *R* are $\frac{^{\circ}\mathrm{F}\times A_u\times \mathrm{h}}{\mathrm{BTU}}$ or $\frac{^{\circ}\mathrm{C}\ \mathrm{x}\ A_u\ \mathrm{x}\ \mathrm{h}}{\mathrm{J}}$. Appendix IX contains *R*-values for some common homogeneous and nonhomogeneous building materials.

The type of construction and the type and amount of insulating material used will determine the rate of heat flow for a particular building or building component. Common building components include walls, doors, windows, floors, ceilings, and roofs. The knowledge of the relative insulating values of different construction materials and of how to put them together to estimate the overall insulating value of

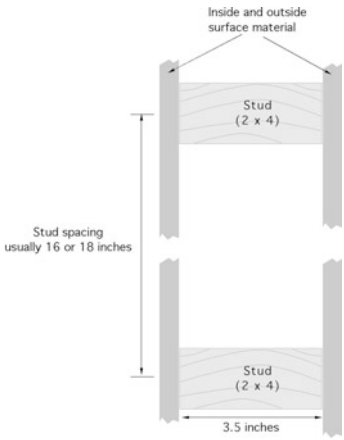

Fig. 22.3 Typical wood frame wall construction viewed looking down

a building or a building component is very helpful in selecting appropriate insulation materials for a particular application.

To determine the total thermal resistance of a wall, simply list and add together the thermal resistance of each part. For homogeneous materials, the total thermal resistance value is determined by the thickness (inches) of the material used times the *R*-value per inch of thickness. For nonhomogeneous materials, select the thermal resistance value for the thickness of material specified.

Two additional factors are important in determining the total thermal resistance of a wall. The first is the thermal resistance associated with the layer of still air next to any surface, as well as any air space. Still air is a good insulating material, and a thin air film clings to exterior and interior surfaces. Air provides a measurable thermal resistance. Typical *R*-values for the inside and outside air film are found in Appendix IX.

The second factor is knowledge of common construction methods. In wood frame construction, the walls are usually made from 2 × 4 or 2 × 6 inch lumber. Lumber is sold using nominal sizes; the actual size is less. A 2 × 4 is actually 1 and 1/2 inches by 3 and 1/2 inches, and a 2 × 6 is actually 1 and 1/2 inches by 5 and 1/2 inches. Frame walls are usually constructed with the long dimension of the board perpendicular to the floor. Different materials are attached to both sides to form the wall. The cavity between the inside and outside surfaces can be filled or partially filled with insulation, see Fig. 22.3.

Problem Determine the total thermal resistance (R_T) of a 2 × 4 wood frame wall. The outside is covered with 1/2 inch medium-density particle board. The vapor barrier is permeable felt. The exterior surface is 2.5 inches of 100 lb per cubic foot fired brick. The inside surface is 1/2 inch plasterboard. The wall is filled with medium-density, loose-fill cellulose.

Solution The *R*-value of the wall is the sum of the *R*-value of each component. For this type of problem, a diagram of the wall and a table of the information will help

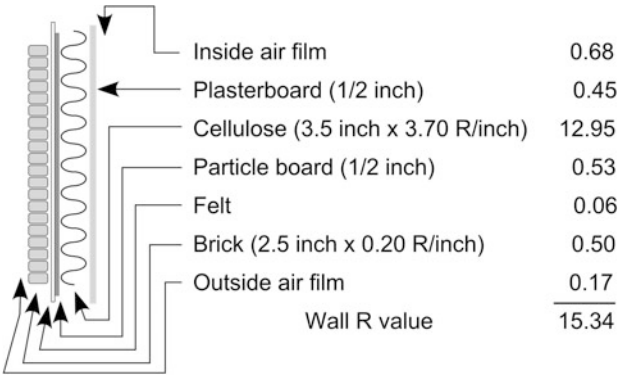
Inside air film 0.68
Plasterboard (1/2 inch) 0.45
Cellulose (3.5 inch x 3.70 R/inch) 12.95
Particle board (1/2 inch) 0.53
Felt 0.06
Brick (2.5 inch x 0.20 R/inch) 0.50
Outside air film 0.17
Wall R value 15.34

Fig. 22.4 Solution to total thermal resistance problem

prevent mistakes. Study Fig. 22.4 for the solution. The *R*-values were obtained from Appendix IX.

For this particular wall, the total thermal resistance (R_T) is 15.34. *Note*: Because loose-fill insulation is used, the thickness of the insulation is equal to the cavity in the wall, 3.5 inches. When a batt type of insulation is used and it is not as thick as the wall, the wall will also have an air cavity or void. The *R*-value for two inside surfaces is used if the air cavity is less than 3/4 inch. For example, if the insulation in the wall in the previous problem is 3.0 inch of low-density batt insulation, then the R_T is 12.71, Table 22.1.

The same table and procedures can be used to determine the total *R*-value for any building component. Simply sum the *R*-values for each type of material and the inside and outside air films. *Note*: Some sources of *R*-values include the air film values with the material.

Problem What is the total *R*-value (R_T) for a ceiling constructed of 1/2-inch plywood for the inside surface with 6.0 inches of low-density batt insulation on top of the plywood?

Solution This problem presents a different situation because neither surface is exposed to outside conditions. In buildings with very low attic ventilation, the

Table 22.1 Solution for insulation problem

Inside air film	0.68
Plasterboard	0.45
Batt (3.0 R/in. × 3.0 in.)	9.00
Cavity (0.68 × 2)	1.36
Particleboard	0.53
Felt	0.06
Brick	0.50
Outside air film	0.17
Total	12.75

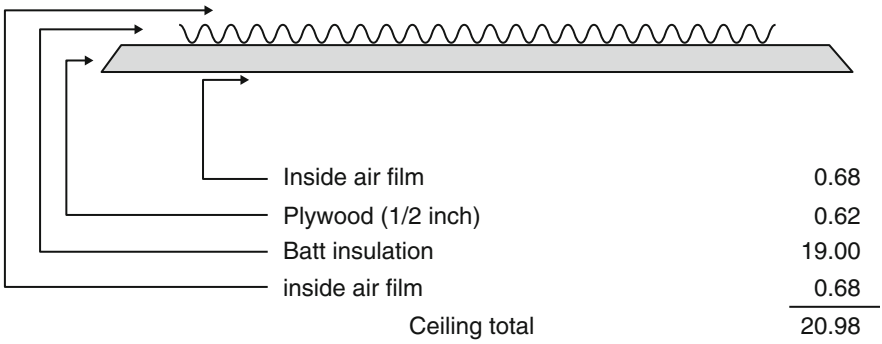

Fig. 22.5 Solution to ceiling total resistance problem

R-value for inside air film should be used on both sides of the ceiling. If the attic is well ventilated, an outside air film *R*-value would be appropriate. For this problem, the assumption is that the attic is not well ventilated.

In this example, the total *R*-value of the ceiling is 20.98, see Fig. 22.5.

It is more difficult to determine the total *R*-value for floors. A concrete slab floor on the ground does not have a uniform temperature gradient across the floor. The insulating properties of the ground will cause the temperatures between the inside space and the ground at the center of the floor to be different from the edges. The values for insulated and uninsulated floors in Appendix IX are estimates.

22.5 Heat Flow

The rate of heat flow through a building component depends upon the thermal resistance of the wall, the temperature difference on both sides of the wall, and the area of the component, expressed as an equation:

$$Q = \frac{A \times \Delta T}{R}$$

where Q = heat flow rate, BTU/h; A = area of building component, ft^2; ΔT = environmental temperature difference on each side of structure, °F; R = total thermal resistance of the building component, $\frac{ft^2 \times {}^{o}F \times h}{BTU}$.

Heat flows from higher temperature to lower temperature. When the inside temperature is greater than the outside temperature, the heat will flow from inside to outside.

Problem Determine the heat flow for an 8.0 × 10.0 ft wall with a total *R*-value of 1.22 and is subject to an inside temperature of 60° F and an outside temperature of 10° F.

Solution

$$Q = \frac{A \times \Delta T}{R} = \frac{(8.0\,\text{ft} \times 10.0\,\text{ft}) \times \left(60^{\circ}\text{F} - 10^{\circ}\text{F}\right)}{1.22\,\frac{\text{ft}^2 \times {}^{\circ}\text{F} \times \text{h}}{\text{BTU}}}$$

$$= 3278.68\ldots \text{or} 3300\,\frac{\text{BTU}}{\text{h}}$$

Heat will move through this wall at the rate of 3300 BTU/h.

The heat flow rate for all building components except floors can be calculated by using this method. If the floor is a concrete slab, the difference in temperature (ΔT) across the floor will change as one moves in from the outside edge of the building. The effective R-values for this type of floor or a concrete slab floor with insulation beneath it can be found in Appendix IX. When either of these two values is used, the perimeter of the building (ft) is substituted for the area (ft^2) in the heat flow equation. If a floor has a crawl space, the total R-value can be calculated by using the same procedures used for a ceiling. Floors over basements are much more complex and will not be discussed in this text.

With the information presented in the previous sections, the total conductive heat flow for a building can be determined. The process for completing a total heat flow calculation is included in a later chapter because total building heat flow must also include heat lost or gained through ventilation.

22.6 SI Problems

Problem Determine the heat flow for a 2.5 m × 3 m wall with a total R-value of 6.93 $\frac{\text{kJ}}{^{\circ}\text{C} \times \text{m}^2 \times \text{h}}$ and is subject to an inside temperature of 16° C and an outside temperature of 12° C.

Solution

$$Q = \frac{A \text{ x } \Delta T}{R} = \frac{(2.5\text{m} \times 3.0\,\text{m}) \text{ x } \left(16^{\circ}\text{C} - 12^{\circ}\text{C}\right)}{6.93\ \frac{\text{m}^2 \times {}^{\circ}\text{C} \times \text{h}}{\text{kJ}}} = 30.30\ldots \text{ or } 30.3\,\frac{\text{kJ}}{\text{h}}$$

Heat will move through this wall at the rate of 30.3 kJ/h.

Chapter 23
Heating, Ventilation, and Air Conditioning

23.1 Objectives

1. Be able to understand the principles of heating
2. Be able to determine a heat balance for a building
3. Be able to list and define the seven physical properties of air
4. Given two properties of air, be able to find the other properties on a psychometric chart
5. Be able to calculate a ventilation rate
6. Be able to understand the principles of air conditioning

23.2 Introduction

Air is a complex mixture of gases, water vapor, and heat. All living organisms require these three components but not necessarily in the same proportions. Each organism has an optimum range of all three conditions, and any time the conditions are less than optimum, the organism is stressed. Management of these components is critical within livestock and some storage structures. Heating, cooling, and ventilation are used to modify the natural environment to reduce the environmental stress of animals and biological products.

The ability to manage building environments is based on an understanding of psychrometrics. Psychrometrics is the study of moist air. The constituents of air and their manipulation are easier to understand using a psychometric chart. The following sections explain the psychometric chart and provide examples of how it is used for heating and ventilation. Computer programs have replaced printed psychometric charts for the design and management of agricultural structures, but knowing and understanding the variables in a computer program are very useful knowledges.

23.3 Psychometric Chart

A psychometric chart is a graphical representation of the seven physical properties of air. These physical properties are defined and described as follows:

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https://doi.org/10.1007/978-3-319-69679-9_23

1. Dry-bulb temperature (dbt): The dry-bulb temperature is the temperature of air measured with a standard thermometer. Dry-bulb temperature is expressed in degrees Fahrenheit (°F) with customary units or degrees Celsius (°C) with SI units.
2. Wet-bulb temperature (wbt): The wet-bulb temperature is determined using a standard thermometer with bulb surrounded by gauze or a sock and a means for keeping the sock wet. As air passes over the wet sock, it will absorb (through evaporation) some of the water from the sock, cooling the bulb of the thermometer. The drier the air, the greater the evaporation and the greater the cooling effect. The difference between the dry-bulb temperature and the wet-bulb temperature is called wet-bulb depression. Dry-bulb and wet-bulb temperatures are measured with an instrument called a psychrometer.
3. Relative humidity (rh): Relative humidity is a ratio of the amount of water in the air relative to the maximum amount of water the air could hold if it were fully saturated. Relative humidity is expressed as a percent, and the values can range from 0% (dry air) to 100% (fully saturated).
4. Moisture content: The moisture content is a measure of the actual amount of water held in the air in the form of vapor. Moisture content is measured in terms of pounds of water per pound of air (lb water/lb air) or grains of water per pound of air (gr. of water/lb air). (*Note*: 7000 grains of water equals 1 pound.) The American Society of Heating and Refrigerating Engineers (ASHRAE) measures moisture in pounds per pound, but some psychrometric charts use grains of water.
5. Dew point: Dew point is the temperature of condensation. It is the temperature that moisture in the air begins to condense or form droplets that are too large to remain suspended in the air. Condensation occurs on any object with a surface temperature equal to or less than the dew point.
6. Total heat: Total heat is the amount of heat energy in the air. It includes heat due to the temperature of the air, sensible heat; the heat required to change water vapor present in the air from liquid to vapor, latent heat; and heat energy in the water vapor itself. The total heat content of air is expressed as BTU per pound of dry air (customary units) or Joules per kg of dry air (SI units).
7. Specific volume: Specific volume is the volume of space occupied by a pound of dry air at standard atmospheric pressure (14.7 psi), expressed in cubic feet per pound of dry air (ft^3/lb air).

23.4 Reading a Psychrometric Chart[1]

A psychrometric chart is designed so that if any two properties of the air are known, values for the other five properties can be found on the chart. Different temperature charts are available. It is common to see high temperature, normal temperature, and

[1]An ASHRAE PSYCHROMETRIC CHART NO. 1 is used in this section. Obtained from American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. 1791 Tullie Circle, NE, Atlanta, Georgia, 30,329. (404–636-8400). If a different chart is used, the values may be different.

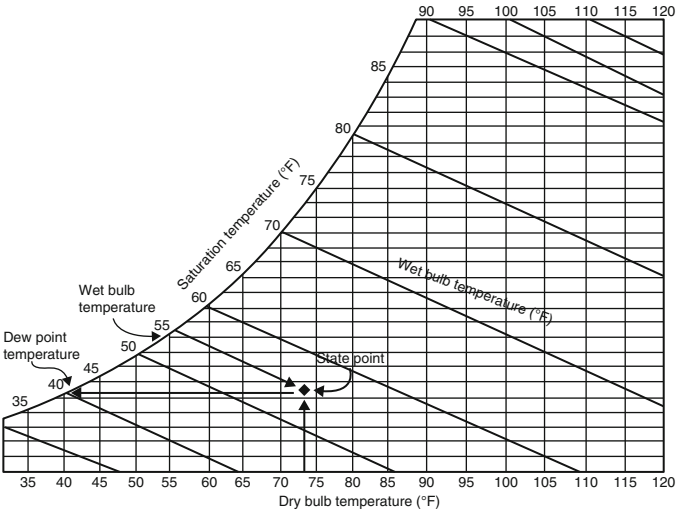

Fig. 23.1 Dry bulb, wet bulb, and saturation temperature scales

low temperature charts. In addition charts are produced for special purposes. To complete the activities of this section, you should obtain a normal temperature psychrometric chart. *Note*: the scales for each property of air are different, and the number of graduations for each scale is not the same. The recommended practice is to interpolate only one decimal point beyond the scale.

A psychrometric chart has a scale and lines for each of the seven properties. To find the values for the properties of air, you must be able to locate what is called the state point. The state point is the junction of any two property lines (Fig. 23.1). The following section will explain how to locate the seven properties of air.

23.4.1 Dry-Bulb Temperature

The dry-bulb temperature scale is located along the bottom of the chart. Dry bulb is easy to measure so it is usually given or known. Locate the temperature, and then move vertically into the chart along the dry-bulb temperature line. In Fig. 23.1 a dry-bulb temperature of 74° was selected.

23.4.2 Wet-Bulb Temperature

The wet-bulb scale is found along the curved side of the chart with the lines leading down and to the right. Locate the wet-bulb temperature along the curved axis, and then follow the line down and to the right until it intercepts with the line of another

known property of the air, for example, the vertical dry-bulb temperature line (Fig. 23.1). If the temperatures of 74°Fdb and 56°Fwb are known, then the state point is located at the junction of these two lines, the "♦" shown in Fig. 23.1. *Note*: the wet-bulb lines are very close to the heat lines. It is easy to confuse the two.

23.4.3 Dew Point

The dew point temperature uses the same scale as the wet-bulb temperature, but movement is horizontal. To locate the dew point value, move horizontally to the left from the state point. For example, in Fig. 23.1, the dew point is 41°F.

23.4.4 Total Heat

The total heat, enthalpy, scale is found by following the total heat lines up from the state point to the left of the wet-bulb scale. The total heat lines and wet bulb lines almost coincide, and this can cause errors in reading the chart, but they use different scales (Fig. 23.2).

23.4.5 Specific Volume

The specific volume scale is located on vertical lines angling up and to the left from the dry-bulb temperature scale. They start at less than 12.5 ft^3/lb in the lower left corner and progress to greater than 15.0 ft^3/lb in the upper right corner of the chart (Fig. 23.2). The values (scale) are contained on the lines.

23.4.6 Relative Humidity

Relative humidity lines follow the curved side of the chart. They progress from 10%, on the line closest to the dry-bulb temperature scale, up to 100%, which is the wet-bulb scale. Notice that the values (scale) are located on the lines, not at the edge of the chart (Fig. 23.3).

23.4.7 Moisture Content

The moisture content scales are usually located on the right side of the chart. To locate a value for moisture, move horizontal to the right from the state point (Fig. 23.3).

A psychrometric chart from the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) or similar group will contain all of seven of these scales. Figure 23.4 is a low precision chart that can be used for learning about psychrometrics and solving the sample problems, but an ASHRAE chart should be used if possible.

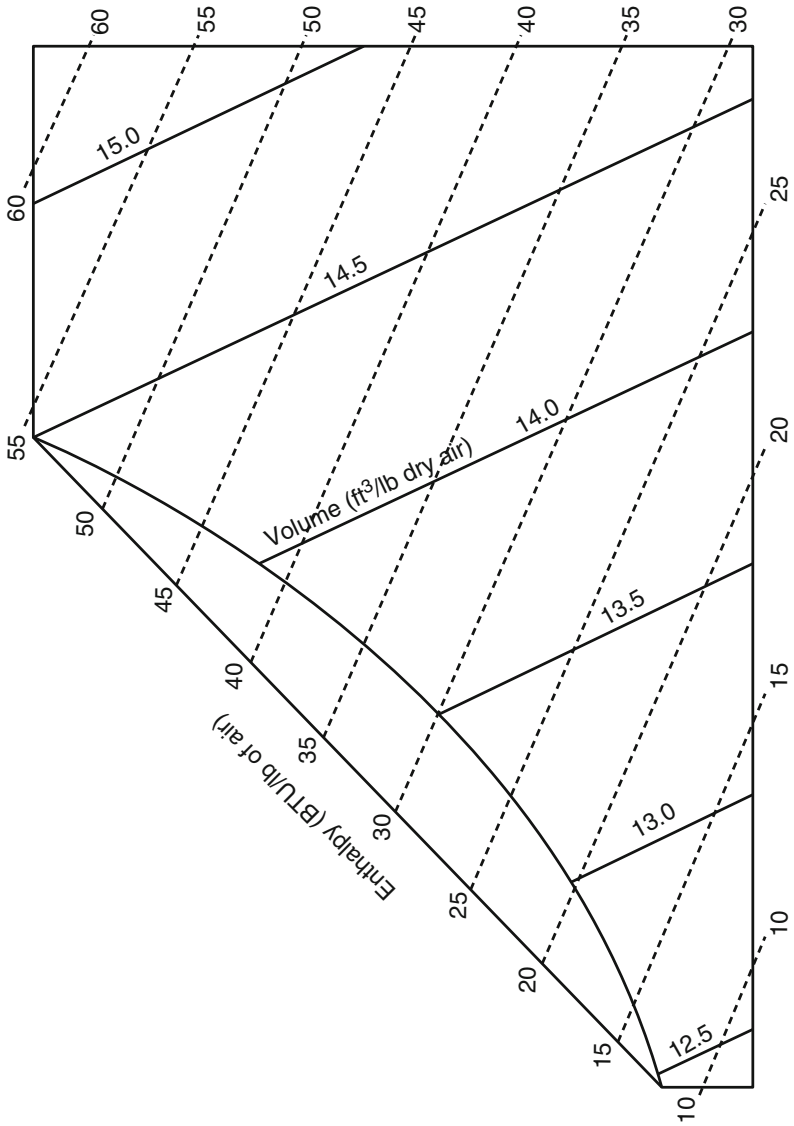

Fig. 23.2 Enthalpy and specific volume scales

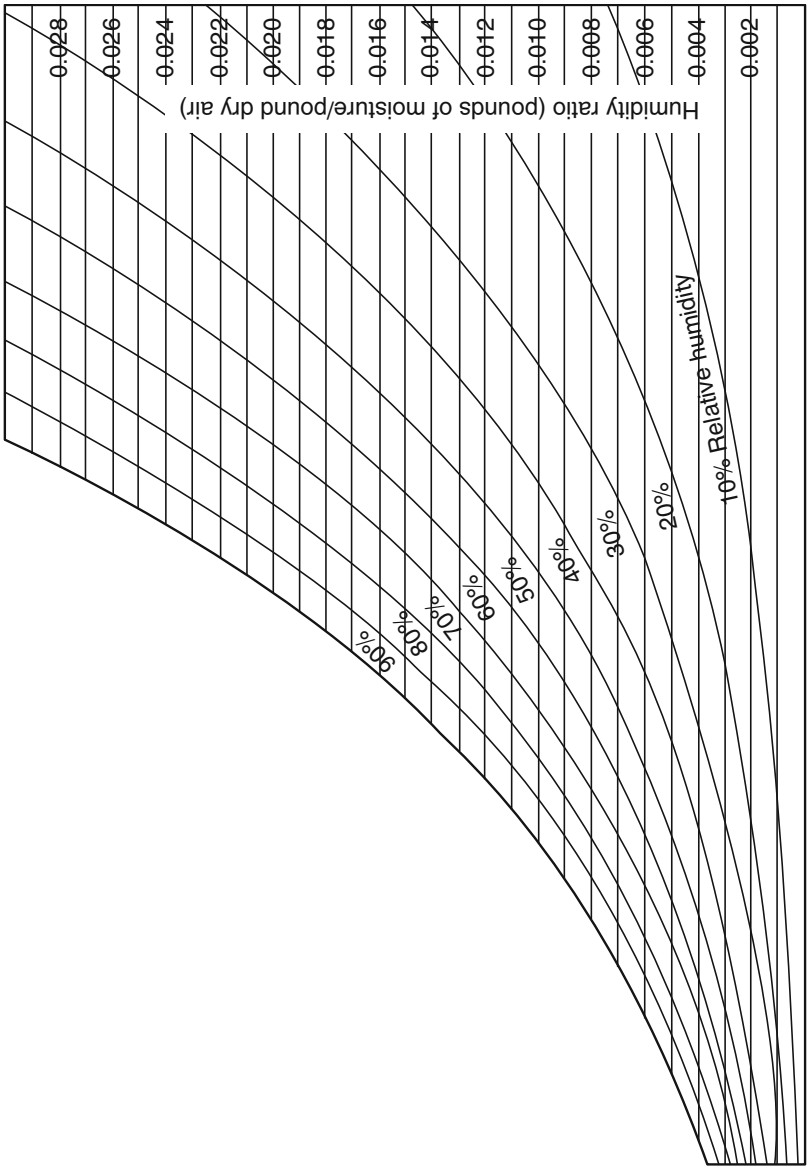

Fig. 23.3 Relative humidity and humidity ratio scales

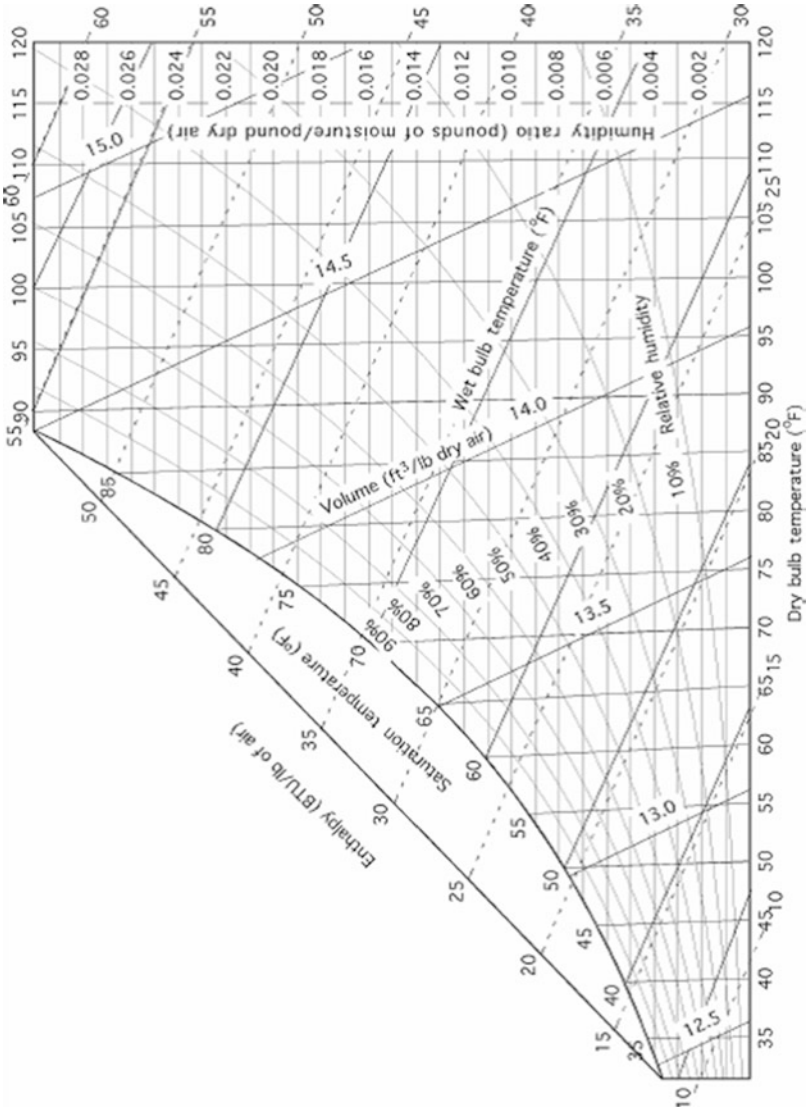

Fig. 23.4 Complete psychrometric chart

Problem What are the physical properties of air if the dry-bulb temperature is 75°F and the wet-bulb temperature is 60°F?

Solution Using a psychrometric chart, Fig. 23.5. [*Note*: not all psychrometric charts are the same. There will be small differences in the readings from different charts produced by different organizations.]

1. The first step is to find the state point. Locate the vertical line that represents the 75°F dry-bulb temperature. Then locate the slanting wet-bulb line that represents 60°F wet-bulb. The intersection of these two lines is the state point.
2. The state point is just above the 40% rh line. Therefore the value of the relative humidity is between 40% and 50%. Because there are no other lines between 40% and 50%, the relative humidity must be estimated or interpolated. This point is estimated as 43% rh.
3. To find the dew point temperature, move horizontally to the left from the state point to the curved wet-bulb and dew point scale. The reading is slightly less than 50°F.
4. To find the moisture content, move horizontally to the right from the state point to the vertical scale. You should read 0.0078 lb of water per pound of dry air.
5. The total heat is found by moving from the state point along the enthalpy line up to the left (parallel to the dashed lines) until the total heat (BTU/lb) scale of air is reached. You should read 27 BTU/lb of air.
6. The specific volume is determined by locating and identifying the specific volume lines (ft^3/lb of dry air) that fall on either side of the state point, which in this case are 13.6 and 13.7. Estimating the state point distance between these lines gives an approximate value of 13.6 ft^3/lb

Psychrometric charts are also used to explain the changes in the properties of air when it is cooled and heated and had water added or water removed.

Problem What are the values for the properties of the air in the previous problem (75°Fdb and 60°Fwb) after the air is heated to 90°Fdb?

Solution The first step is to determine the direction and the distance to move from the first state point to the second state point. In this problem, because heat is added and the moisture content is not changed, the second state point is located to the right of the first along the horizontal moisture line. Move right until this line intersects with the vertical 90°Fdb line, and then read the values for the characteristics at the second state point (Fig. 23.6).

The values are:

Heat = 30.0 BTU/lb	Dew point = 49 °F
Specific volume = 14.05 ft^3/lb	Moisture = 0.0076 lb/lb
Relative humidity = 27%	Wet bulb = 65 F

Compare these results with those for the previous problem. When you understand the principles of air illustrated by a psychrometric chart, you should be able to

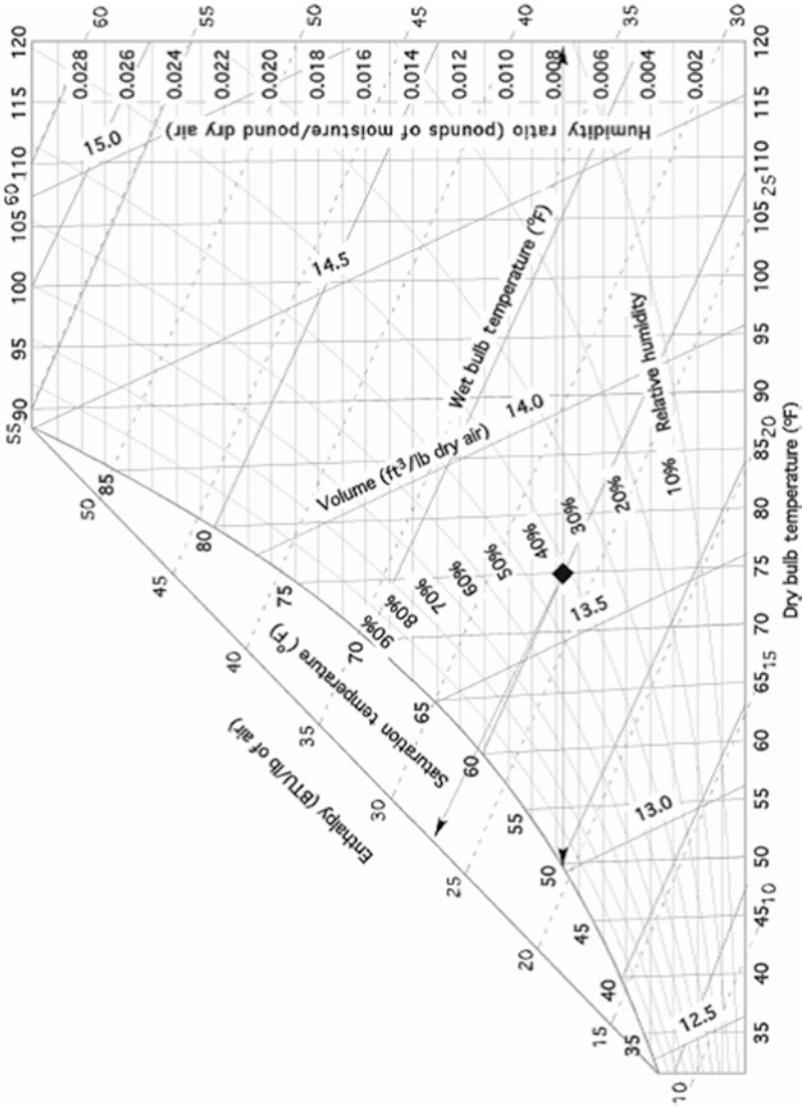

Fig. 23.5 Psychrometric chart for problem one

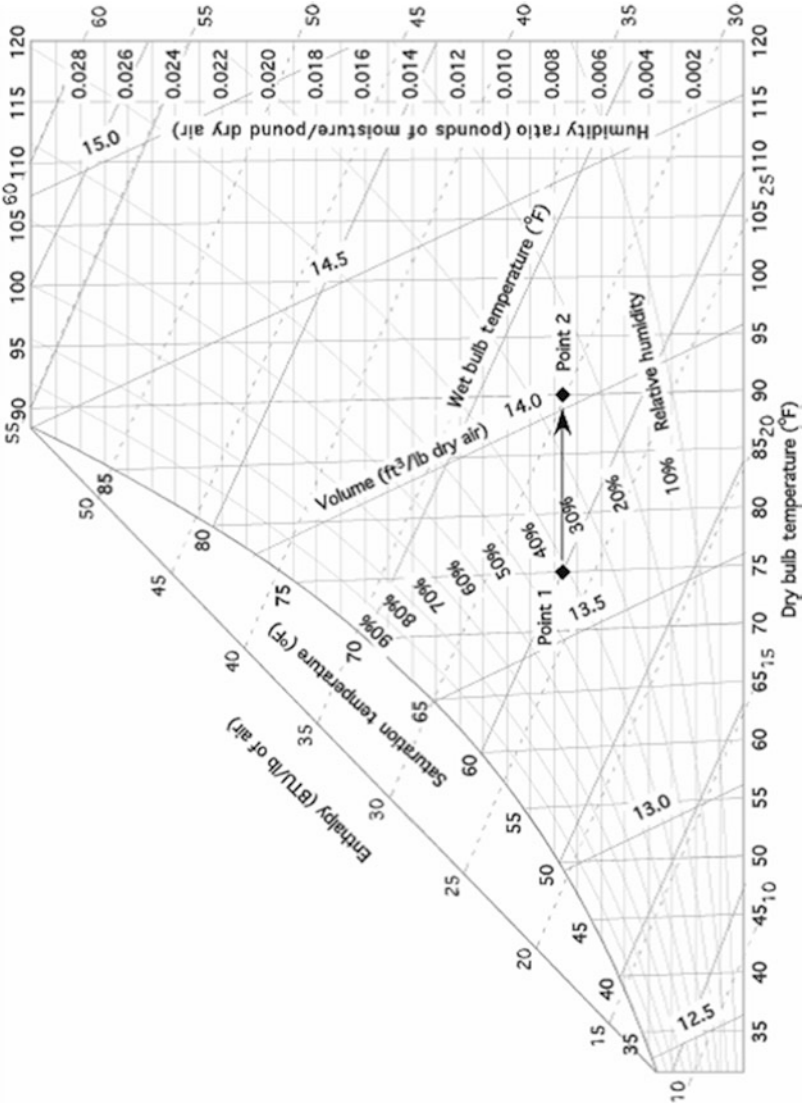

Fig. 23.6 Psychrometric chart for problem two

explain why the values for some of the characteristics changed and why some did not.

23.5 Heating

Heating is used to modify an environment by raising the dry-bulb temperature or to offset the effects of heat loss from a building. The amount of heat required depends upon the use of the building (animal housing, product storage, etc.), the heat flow out of the building, the ventilation needed, and the sources of heat within the building. In buildings used for product storage, ventilation rates may be at a minimum, or no ventilation may be needed. Livestock housing must be ventilated to remove the moisture given off by the animals as they breathe and the harmful gases that can develop in the building.

23.6 Ventilation Rate

Ventilation is the movement of air through a building. The movement may be caused by natural convection, by wind, or by forcing air movement with fans. Air is used to remove moisture, reduce the temperature if the outside air is cooler than the inside, and replace gases inside the building with outside air. The minimum ventilation rate is determined by which purpose of ventilation has the greatest requirement. For livestock buildings, if the ventilation rate is sufficient to remove excess moisture, it usually will meet and exceed the rate necessary for other needs.

In this section, a procedure involving the use of a psychrometric chart is used to make estimates of the amount of ventilation required to remove the excess moisture from a livestock building. For buildings used for other purposes, the critical environmental condition must be determined. The calculations for ventilation are based on the need for that factor. Appendix X contains values for moisture and heat released by different animals and the heat produced by mechanical equipment.

When outside air is introduced into a building, it must be uniformly distributed within the building and mixed with the building air to prevent drafts. One method is to introduce the air through small openings distributed around or throughout the building. Another method is to use heat exchangers. A heat exchanger uses the heat of the exhaust air to preheat incoming air, thus reducing the chilling effects of drafts and reducing the amount of heat loss by ventilation. Actual airflow rates required for animal buildings will vary with the type and size of animal, management system, type of floor and floor drainage, and the number of animals in the building.

As moisture evaporates into the air, it changes the physical properties of the air. The amount of change can be determined by locating the state points for both conditions. The numerical differences in the moisture content and the total heat of both conditions provide the information used to determine the amount of air and the heat required to evaporate the moisture.

Table 23.1 Psychrometric data for ventilation problem

Properties	Inside	Outside	Difference
Dry bulb (°F)	55	40	
Wet bulb (°F)	48	35	
Moisture (lb H_2O/lb of air)	0.0054	0.0028	0.0026
Total heat (BTU/lb)	19.00	13.0	6.0
Specific volume (ft^3/lb of air)	13.1	12.65	

Problem How much air and heat will be needed to evaporate 2.0 lb of water per hour from within a building when the inside air temperature is 55°F dry bulb (db) and 48°F wet bulb (wb) and the outside air conditions are 40°Fdb and 35°Fwb?

Solution In this problem we will use values for five of the properties of air for two different air conditions. Constructing a table, Table 23.1, is very helpful and is recommended for solving problems of this type.

The first step is to use the psychrometric chart to find the values for moisture content, total heat, and specific volume for both the inside and outside air. These values are recorded in the columns "Inside" and "Outside." *Note*: the values used are from the chart in Fig. 23.4. Numbers from an ASHRAE chart will be slightly different. An ASHRAE or similar chart should be used when solving a real problem.

The next step is to determine the differences in moisture content and in total heat between the inside and the outside air. These values are recorded in the column labeled "Difference." Values for the differences in temperature and in specific volume are not needed in this problem.

The third step is to determine the amount of air (lb) required to remove the moisture. The amount of air required to evaporate the moisture is determined from the difference in the moisture content of the inside and the outside air. A difference of 0.0026 lb of water per pound of air means that every pound of outside air brought in and raised to inside conditions is capable of absorbing 0.0026 lb of moisture. If each pound of air absorbs the maximum amount of water, 0.0026 lb, and the amount of water that must be removed is 2.0 lb per hour, then the required amount of air (lb) is:

$$\frac{\text{lb air}}{\text{h}} = \frac{1 \text{ lb air}}{0.0026 \text{ lb water}} \times \frac{2.0 \text{ lb}}{1 \text{ h}} = 769.23\ldots \quad \text{or } 770 \frac{\text{lb air}}{\text{h}}$$

For these inside and outside conditions, 770 lb of air per hour moving through the building will be needed to remove 2.0 lb of water per hour, assuming that the air absorbs the maximum amount of water.

Before water in liquid form can be absorbed by air, it must be vaporized and this requires heat. In addition, if the inside of the building is warmer than the outside, ventilation also causes a loss of heat from the building. The total amount of heat loss is determined by using the difference in the heat of the incoming and the outgoing air. The amount of heat in the inside air is 19.0 BTU/lb, and the heat of the

outside air is 13.0 BTU/lb, a difference of 6.0 BTU/lb. This amount of heat will be lost with each pound of air ventilated. We have already determined that 770 lb of air per hour will be needed to evaporate the water produced in the building; so the heat loss due to ventilation is:

$$\frac{\text{BTU}}{\text{h}} = 770\ \frac{\text{lb air}}{\text{h}} \times \frac{6.0\ \text{BTU}}{\text{lb air}} = 4620 \quad \text{or} \quad 4600\,\frac{\text{BTU}}{\text{h}}$$

For these conditions, 4600 BTU per hour of heat will be transported outside the building with the ventilation air.

Ventilation fans usually are sized in units of cubic feet per minute. This will require a unit conversion from weight to volume. This conversion is made using the specific volume values from the psychrometric chart. When the ventilation fan is exhausting building air (the most common situation), the inside specific volume is used. If the fan is blowing in outside air, the outside specific volume is used. Because it takes 770 lb of air per hour to evaporate the water produced in the building, the volume of air (ft^3/h) that is required is determined by multiplying the pounds of air per hour by the specific volume. The size of fan required is:

$$\frac{\text{ft}^3}{\text{h}} = 770\ \frac{\text{lb air}}{\text{h}} \times 13.1\ \frac{\text{ft}^3}{\text{lb air}} = 10{,}087 \text{ or } 10{,}000\,\frac{\text{ft}^3}{\text{h}}$$

A fan or several fans with a combined capacity of 10,000 cubic feet per hour are required to provide enough ventilation to remove the excess moisture from the building.

The values calculated in the previous problem are accurate only as long as the inside and the outside environments do not change. This only occurs for short periods of time because the outside temperature is constantly changing, the respiration rate of the animals changes with activity, and heat exchanges also occur because of conduction, convection, and radiation. Heating, ventilating, and cooling systems must be able to react to change, and if they are required to maintain a constant inside environment, they must have the capacity for the most extreme inside and outside situations.

23.7 Building Heat Balance

The principles of heating, ventilation, and air conditioning are all used to determine the amount of ventilation, heat, or air conditioning needed to maintain the temperature inside a building. The process of calculating the changes that occur in the environment inside a structure is called a heat balance. Expressed mathematically a heat balance is:

$$\pm\text{Heat}\left(\frac{\text{BTU}}{\text{h}}\right) = \text{Total heat gain } (H_\text{G}) - \text{Total heat loss } (H_\text{L})$$

Three possible answers can result from using the heat balance eq.: (1) The amount of heat gain is larger than the heat loss. This will result as a positive (+) heat gain. In this situation the temperature of the building will increase. (2) The heat

gain and heat loss are the same. When this is true, the answer from the heat balance equation is zero, and the temperature within the building will remain stable. (3) The heat loss is greater than heat gain. When this is true, the answer for the equation is negative (−), and the temperature inside the building will decrease.

The four factors needed to determine heat gain or loss are mechanical equipment heat, animal heat, heat flow, and ventilation. Mechanical equipment, such as electric motors and heat lamps, and animals put heat into the building. Heat flows from areas of high temperature to areas of low temperature. The term heat flow is used to describe the movement of heat through the components of a building. Ventilation and its effect on the environment are discussed in a previous section.

These factors usually result in either a heat gain or a heat loss, depending on the season of the year and the temperatures. For a winter heat balance, the heat gain is the sum of the animal heat and the mechanical equipment heat, and the heat losses are due to heat flow and ventilation.

$$\pm \text{Heat}_{\text{W}} = (\text{Animal heat} + \text{Mechanical heat}) - (\text{Heat flow} + \text{Ventilation})$$

For a summer heat balance, the heat gain is the sum of the animal heat, mechanical equipment heat, and heat flow.

$$\pm \text{Heat}_{\text{S}} = (\text{Animal heat} + \text{Mechanical heat} + \text{Heat flow}) - (\text{Ventilation})$$

The following problem illustrates the procedure for calculating a winter heat balance for a building. *Note*: in this calculation the effects of radiation are ignored.

Problem Determine the daytime heat balance (BTU/h) for a 30.0 ft by 60.0 ft structure with 8.0 ft walls, which houses two hundred 150.0 lb feeder pigs. The building has two, 3.0 f. by 6.6 f. pine doors, 1.0 inch thick. In addition, it has ten 24.0 inch by 42.0 inch single-pane windows. The walls are 8.0 inch lightweight concrete block with the cores filled with lightweight perlite. The ceiling is 3/8 inch plywood with 6.0 inches of low-density batt insulation between the joists. The mechanical equipment includes nine 100 W incandescent lights that operate 10 h per day, two 1/3 horsepower auger motors which operate 30 min per day, and ten 1/4 horsepower ceiling fans that operate 5 h per day. The attic space is well ventilated and is at the same temperature as the outdoors. The building is on an insulated concrete slab. The temperatures are 70°Fdb and 60°Fwb inside and 40° Fdb and 34° Fwb outside.

Solution Two values are required to determine a heat balance—the total heat loss and the total heat gain. Begin by determining total heat loss. For winter conditions, total heat losses are heat flow and ventilation.

Heat losses: The heat flow equation used in the previous chapter is used to determine the total heat flow into or out of a building. The total heat flow is found by calculating and summing the heat flow for each component of the building having a unique *R*-value. The different *R*-values in this problem include those of the walls, windows, door, ceiling, and floor. Errors can be reduced by setting up a table of the required information. Because heat flow is a function of area, temperature difference, and thermal resistance, table columns are included for this information

Table 23.2 Solution for building heat flow problem

Component	Total *R*-value	Area (ft^2)	ΔT (°F)	Q (BTU/h)
Walls (less openings)	7.65	1330.4	30	5217.25...
Windows	0.91	70.0	30	2307.69...
Doors	1.85	39.6	30	642.16...
Ceiling	20.32	1800	30	2657.48...
Floor	2.22	180[a]	30	2432.43...
		Total heat flow (Q_T) =		13,257.02...

[a]The perimeter (ft) is used for slab floors, not the area (ft^2)

(Table 23.2). In addition, it may be helpful to sketch components, as in the example in Chap. 22. A sketch was not used in this example because each building component has a small number of parts. Using the conduction heat flow equation:

$$Q = \frac{A \times \Delta T}{R}$$

where Q = heat flow, BTU/h; A = area of structure with similar R-value, ft^2; ΔT = difference in temperature between inside and outside, °F; R = thermal resistance of the building component.

With a temperature difference of 30 F, the total heat loss is 13,200 BTU/h. These numbers were calculated as follows:

R-values		
Wall	Outside air film	0.17
	Concrete blocks, filled cores	6.8
	Inside air film	0.68
	Total *R*-value for wall	7.65
Windows	Outside air film	0.17
	Single-pane glass	0.06
	Inside air film	0.68
	Total *R*-value for windows	0.91
Door	Outside air film	0.17
	Wood	1.00
	Inside air film	0.68
	Total *R*-value for door	1.85
Ceiling	Inside air film	0.68
	Insulation (6-in batt)	19.00
	Plywood	0.47
	Outside air film	0.17
	Total *R*-value for ceiling	20.32
Floor	Insulated concrete	2.22

Areas:
The wall area is minus the doors and windows; they will be calculated first.
Windows:

$$\begin{aligned} \text{ft}^2 &= [(24.0\ \text{in} \times 42.0\ \text{in}) \times 10] \times \frac{1\ \text{ft}^2}{144\ \text{in}^2} \\ &= 70.0\ \text{ft}^2 \end{aligned}$$

Doors:

$$\begin{aligned} \text{ft}^2 &= 3.0\ \text{ft} \times 6.6\ \text{ft} \times 2 \\ &= 39.6\ \text{ft}^2 \end{aligned}$$

Wall:

$$\begin{aligned} \text{ft}^2 &= (\text{area of endwalls} + \text{area of side walls}) - (\text{area of windows} + \text{area of doors}) \\ &= [(8.00\ \text{ft} \times 30.0\ \text{ft} \times 2) + (8.00 \times 60.0\ \text{ft} \times 2)] - \left(70.0\ \text{ft}^2 + 39.6\ \text{ft}^2\right) \\ &= \left(480\ \text{ft}^2 + 960\ \text{ft}^2\right) - 109.6\ \text{ft}^2 \\ &= 1440\ \text{ft}^2 - 109.6\ \text{ft}^2 = 1330.4\ \text{ft}^2 \end{aligned}$$

Ceiling:

$$\begin{aligned} \text{ft}^2 &= \text{Length} \times \text{Width} = 60.0\ \text{ft} \times 30.0\ \text{ft} \\ &= 1800\ \text{ft}^2 \end{aligned}$$

Floor perimeter:

$$\begin{aligned} \text{ft} &= (\text{Length} \times 2) + (\text{Width} \times 2) = (60.0 \times 2) + (30.0 \times 2) \\ &= 180\ \text{ft} \end{aligned}$$

Building heat flow (Q_T):

$$\begin{aligned} Q_\text{T} &= Q_\text{wall} + Q_\text{window} + Q_\text{door} + Q_\text{ceiling} + Q_\text{floor} \\ &= \frac{1330 \times 30.0}{7.65} + \frac{70.0 \times 30.0}{0.91} + \frac{39.6 \times 30.0}{1.85} + \frac{1800 \times 30.0}{20.32} + \frac{180 \times 30.0}{2.22} \\ &= 5217.25\ldots + 2307.69\ldots + 642.16\ldots + 2657.48\ldots + 2432.43\ldots \\ &= 13{,}257.02\ldots \text{ or } 13{,}200\frac{\text{BTU}}{\text{h}} \end{aligned}$$

Table 23.3 Psychrometric data for problem

Properties	Inside	Outside	Difference
Dry bulb (°F)	70.0	40.0	
Wet bulb (°F)	60.0	34.0	
Moisture (lb/lb)	0.0088	0.0026	0.0062
Total heat (BTU/lb)	26.5	12.5	13.5
Specific volume (ft^3/lb)	13.6	12.6	

This is a wintertime heat balance, so ventilation is a source of heat loss. The ventilation heat loss is determined by the ventilation rate required to remove the excess moisture from the building and the difference in temperature between the inside and the outside air. A table should be used to organize the psychrometric data (Table 23.3).

In this problem, the building is used to house livestock. Therefore, the ventilation rate will be determined by the amount of water vapor produced by the animals. Appendix X contains values that can be used to estimate the amount of heat and moisture produced by various animals, based on weight and species.

To determine the ventilation rate, begin by finding the amount of water released into the building. A 150 lb feeder pig produces 0.219 lb of moisture per hour, Appendix X. The total water produced is:

$$\frac{\text{lb}}{\text{h}} = \frac{0.219 \ \frac{\text{lb } H_2O}{\text{h}}}{\text{pig}} \times 200 \text{ pigs} = 43.8 \ \frac{\text{lb } H_2O}{\text{h}}$$

Next, determine the amount of air needed to remove 43.8 lb of water per hour. This is accomplished by multiplying the amount of water that each pound of air can absorb as it passes through the building by the amount of water that needs to be removed. If the air is 100% saturated when it leaves the building, the amount of water that the air will remove is determined by the difference between the moisture content of the air entering and that of the air exiting the building. From Table 23.3, this value is 0.0062 lb of water per pound of dry air. The amount of air needed is:

$$\frac{\text{lb air}}{\text{h}} = \frac{1 \text{ lb air}}{0.0062 \text{ lb water}} \times \frac{43.8 \text{ lb water}}{\text{h}} = 7064.51\ldots \text{ or } 7060 \ \frac{\text{lb air}}{\text{h}}$$

Now that the ventilation rate is known, the amount of heat loss due to ventilation can be calculated. This is accomplished by multiplying the pounds of air per hour that will be moving through the building by the difference between the amount of heat in the inside air and the heat in the outside air. From Table 23.3, this value is 13.5 BTU/lb of air. The heat loss due to ventilation is:

$$\frac{\text{BTU}}{\text{h}} = 7060\ \frac{\text{lb air}}{\text{h}} \times 13.5\,\frac{\text{BTU}}{\text{lb air}} = 95{,}310\ \text{ or }\ 95{,}300\,\frac{\text{BTU}}{\text{h}}$$

The total heat loss is obtained by adding the rates for heat flow and ventilation:

$$\begin{aligned}\frac{\text{BTU}}{\text{h}} &= \text{Heat flow} + \text{Ventilation losses}\\ &= 13{,}300\,\frac{\text{BTU}}{\text{h}} + 95{,}300\,\frac{\text{BTU}}{\text{h}}\\ &= 108{,}600\,\frac{\text{BTU}}{\text{h}}\end{aligned}$$

Heat gain: Next determine the total heat gain. The sources of heat are the mechanical equipment and the heat given off by the animals, Appendix X.

Mechanical equipment:

$$\begin{aligned}\text{Heat gain}\,\frac{\text{Btu}}{\text{h}} &= \text{Mechanical heat} + \text{animal heat}\\ \text{Mecahnical heat} &= \text{Lights} + \text{Motors}\\ \text{Lights} &= \left(9\ \text{lights} \times 100\ \frac{\text{watt}}{\text{light}} \times 3.4\,\frac{\text{Btu}}{\text{watt-h}}\right) = 3060\,\frac{\text{Btu}}{\text{h}}\\ \text{Motors} &= \left(2\ \text{motors} \times 0.33\,\frac{\text{hp}}{\text{motor}}\right) + \left(10\ \text{motors} \times 0.25\,\frac{\text{hp}}{\text{motor}}\right)\\ &= \left(0.66\ \frac{\text{hp} - \text{h}}{\text{day}} + 2.5\ \frac{\text{hp} - \text{h}}{\text{day}}\right) \times 4000\,\frac{\text{Btu}}{\text{hp} - \text{h}}\\ &= 12{,}640\,\frac{\text{Btu}}{\text{day}}\\ \text{Mechanical heat} &= 3060\,\frac{\text{Btu}}{\text{day}} + 12{,}640\,\frac{\text{Btu}}{\text{day}}\\ &= 15{,}700\,\frac{\text{Btu}}{\text{day}}\\ \text{Animal heat}\ \frac{\text{BTU}}{\text{h}} &= \frac{354\ \text{BTU}}{\text{pig}} \times 200\,\text{pigs} = 70{,}800\,\frac{\text{BTU}}{\text{h}}\\ \text{Heat gain} &= \text{Mechanical heat} + \text{Animal heat}\\ &= 15{,}700\,\frac{\text{Btu}}{\text{h}} + 70{,}800\,\frac{\text{Btu}}{\text{h}}\\ &= 86{,}500\,\frac{\text{Btu}}{\text{h}}\end{aligned}$$

Heat balance: All of the information needed to complete the heat balance is available.

$$\pm\text{Heat balance } \frac{\text{BTU}}{\text{h}} = \text{Total heat gain} - \text{Total heat loss}$$
$$= 86{,}500\,\frac{\text{BTU}}{\text{h}} - 108{,}600\,\frac{\text{BTU}}{\text{h}}$$
$$= -22{,}100\,\frac{\text{BTU}}{\text{h}}$$

A heat balance with a negative number indicates that the amount of heat gain in the building is less than the amount of heat being lost from the building. When this occurs, the temperature inside the building will decrease unless additional heat is added. For this problem 22,100 BTU/h of heat is needed to maintain the inside temperature of the building. *Note*: livestock building environments are dynamic systems. The heat gain and loss are never constant. In this problem the heat balance was calculated with the assumption that the auger motors and ceiling fans were operating. The auger motors only operate 30 min a day. What happens to the heat balance when they are turned off? What is the effect of turning off some of the ceiling fans or if one of the waterers develops a leak?

23.8 Air Conditioning

In some types of buildings, ventilation may not be adequate to maintain the optimum temperature. The amount of heat produced by the animals, the processing, the outside temperatures, and so on may exceed the ability of the ventilation system to maintain the desired temperature. In these situations air conditioners are used.

Historically many different systems have been used to condition the air. Cooling with ice, pumping well water through a radiator, and evaporative cooling or drawing air through underground tubes have all been used. Mechanical refrigeration has replaced these systems. The use of ice produces large amounts of cooling, but the resulting water must be disposed of, and a continuous supply of ice must be available. Pumping well water through a radiator uses a lot of energy for the cooling produced, but using the energy stored in groundwater is used by ground source heat

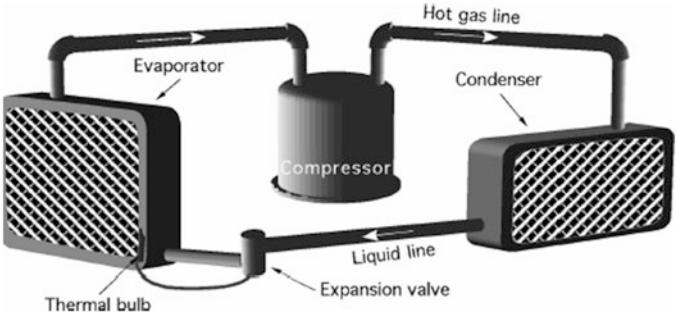

Fig. 23.7 Mechanical refrigeration system

pumps. Evaporative cooling is effective only if the outside air has a low relative humidity.

Today, the term air conditioning refers to conditioning air through the use of mechanical refrigeration. Refrigeration is the process of transferring heat from one substance to another. For air conditioning refrigeration moves heat from the air inside a structure to the air outside the structure. For this to occur the hot outside air must come in contact with a material at a temperature lower than the inside air. When this happens, heat from the air will flow into the colder material. Some air conditioners use a chilled metal surface to provide a cold mass, whereas others use a spray of chilled water. The heat is transferred by a substance circulating between the inside air and the outside air. In smaller units the transfer substance will be a gas; for larger systems, the substance may be a liquid. Figure 23.7 is an illustration of the basic components of a gas mechanical refrigeration system.

In a mechanical refrigeration system, heat is moved by alternately compressing, liquefying, expanding, and evaporating a refrigerant. The compressor increases the pressure and the temperature of the refrigerant as it compresses the gas. As the refrigerant passes through the condenser, the heat absorbed by the refrigerant as it passed through the evaporator and the heat produced by compression are transferred into the air. Thus, the condenser will be located where outside air moving across it absorbs the heat causing the refrigerant to liquefy. As the liquid refrigerant flows through the expansion valve and into the evaporator, the pressure drops and the refrigerant absorbs heat from the surrounding air. The evaporator will be located inside an air duct or other location where air can pass through it and be cooled, causing the refrigerant to be vaporized. The hot, low-pressure gas flows back to the compressor, and the cycle begins again. The expansion valve and a thermal bulb regulate the flow of the refrigerant to produce the desired evaporator temperature.

It is common for mechanical refrigeration air conditioning to lower the temperature 20 to 30°. Often this results in an air temperature that is below the dew point. This is the reason building and automobile air conditioners produce water. This can be shown on a psychrometric chart.

Problem How many pounds of water will be removed per pound of dry air when air at 95°Fdb and 70% rh is cooled to 75°Fdb?

Solution The solution is mapped out in Fig. 23.8.

Locate the initial state point on a psychrometric chart. Air conditioning lowers the dry-bulb temperature, so move left to 75°. As the air is cooled, the relative humidity increases, and in this example the saturation point is reached before 75°. In this situation follow the saturation line down to 75°. This is the second state point. The amount of water removed is the difference in the humidity ratio between state point one and state point two.

$$\frac{\text{lb } H_2O}{\text{lb dry air}} = 0.0254 \frac{\text{lb } H_2O}{\text{lb dry air}} - 0.019 \frac{\text{lb } H_2O}{\text{lb dry air}} = 0.0064 \frac{\text{lb } H_2O}{\text{lb dry air}}$$

Evaporative cooling is still useful for reducing the temperature of air in climates where the relative humidity is low. An evaporative cooler pulls outside air through a

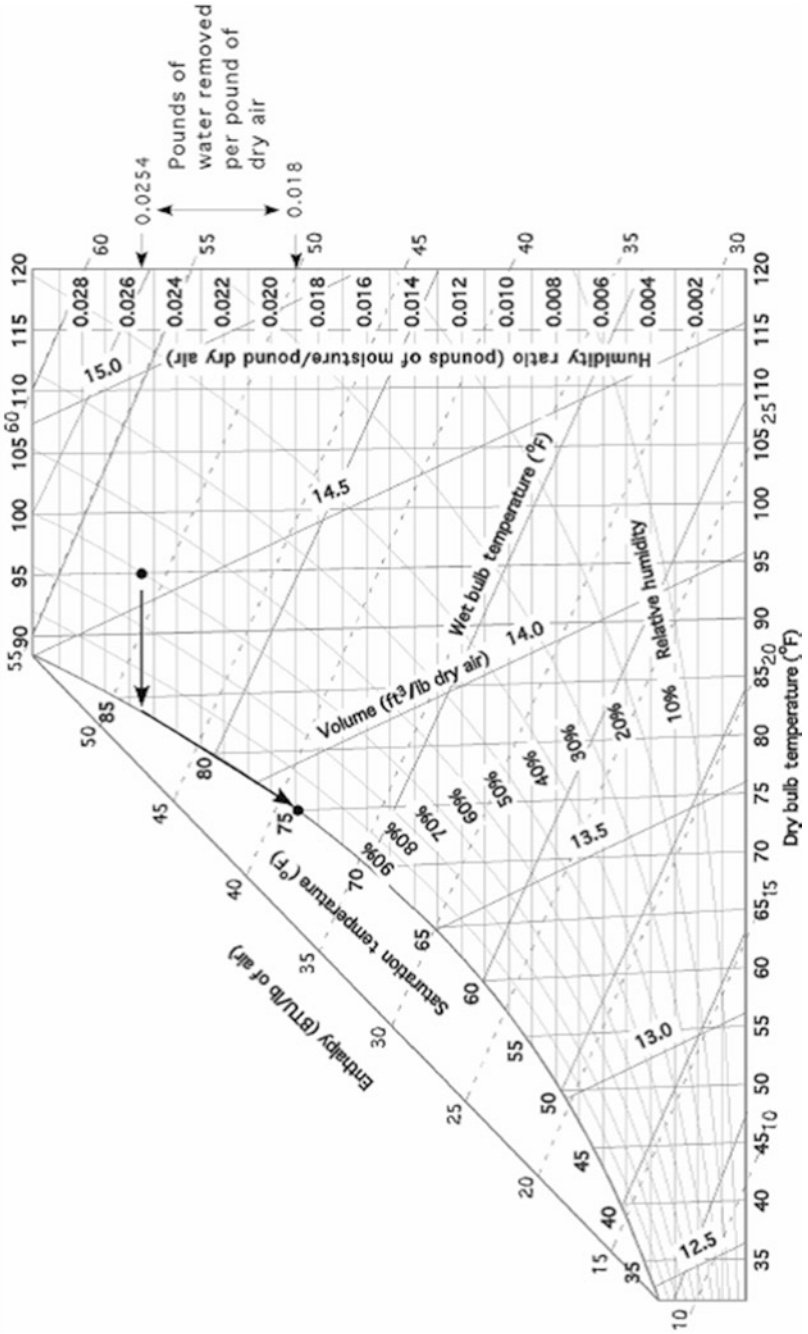

Fig. 23.8 Solution for air conditioning problem

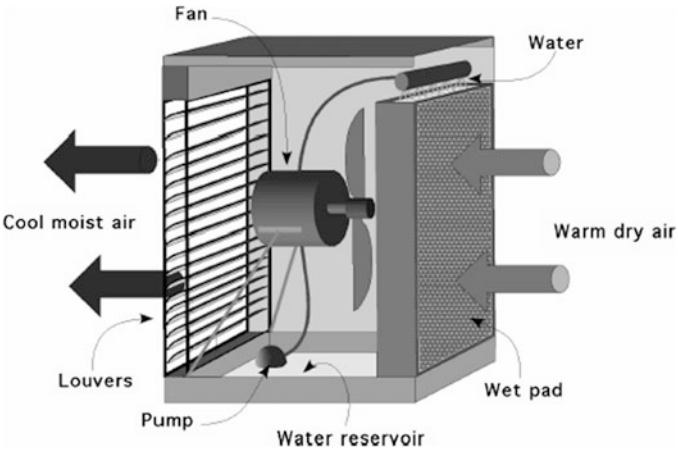

Fig. 23.9 Evaporator cooler

wet pad of porous material. As the air passes through the pad, the temperature of the air causes water to evaporate, lowering the temperature and raising the relative humidity. Figure 23.9 illustrates the components of a window or portable unit.

The larger systems used in greenhouses and other structures have similar components. The principles of evaporative cooling can be demonstrated using a psychrometric chart.

Problem Determine the amount of reduction in the temperature of air that is at 100°Fdb and 40% rh after it passes through an evaporative pad and becomes 90% saturated.

Solution Figure 23.10 shows the solution mapped out on the psychrometric chart.

Start by locating state point number one. In evaporative cooling water is converted from liquid to a vapor. This requires heat. The heat for evaporation is drawn from the air, which lowers the dry-bulb temperature. Lowering the dry-bulb temperature is represented by moving horizontally to the left from state point number 1. But evaporative cooling also adds water vapor to the air. Adding water vapor to the air is represented by moving vertically up the chart

Table 23.4 Comparison of customary and SI psychrometric terms

Term	Conventional	SI
Relative humidity	%	%
Specific Volume	ft^3/lb	m^3/kg
Dry bulb	°F	°C
Wet bulb	°F	°C
Enthalpy	Btu/lb dry air	kJ/kg dry air
Dew point	°F	°C
Moisture content	lb H_2O/lb dry air	kg H_2O/kg dry air
Time	hour	hour

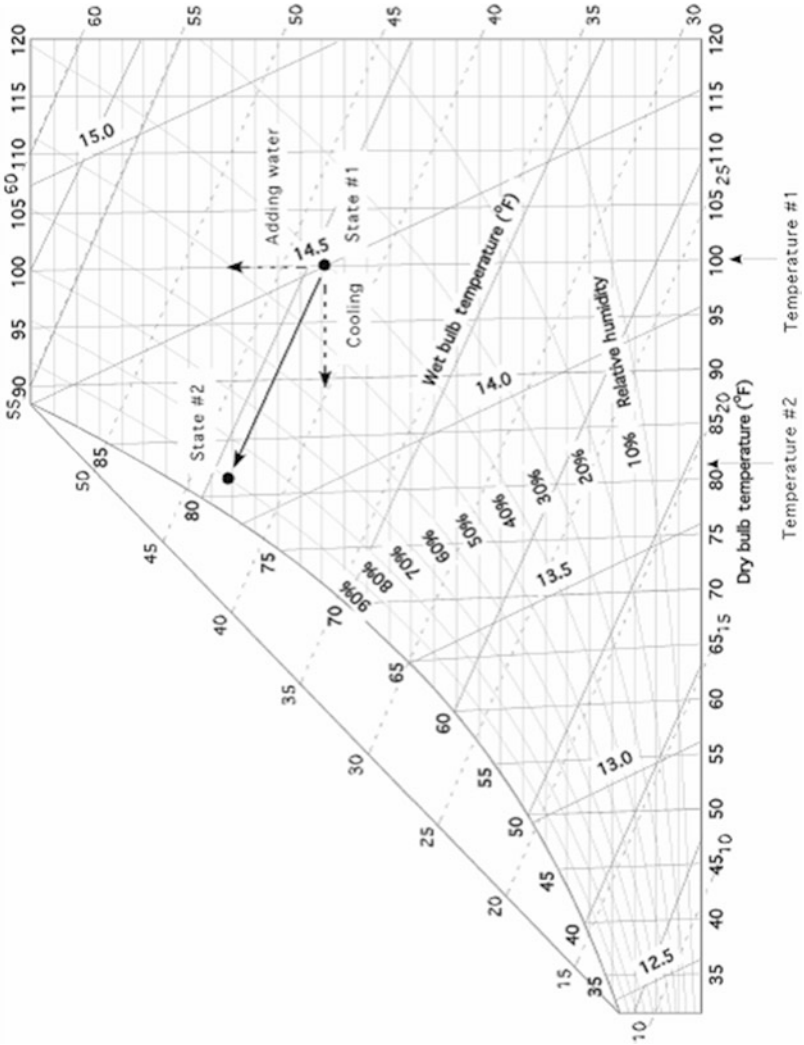

Fig. 23.10 Solution for evaporating cooling problem

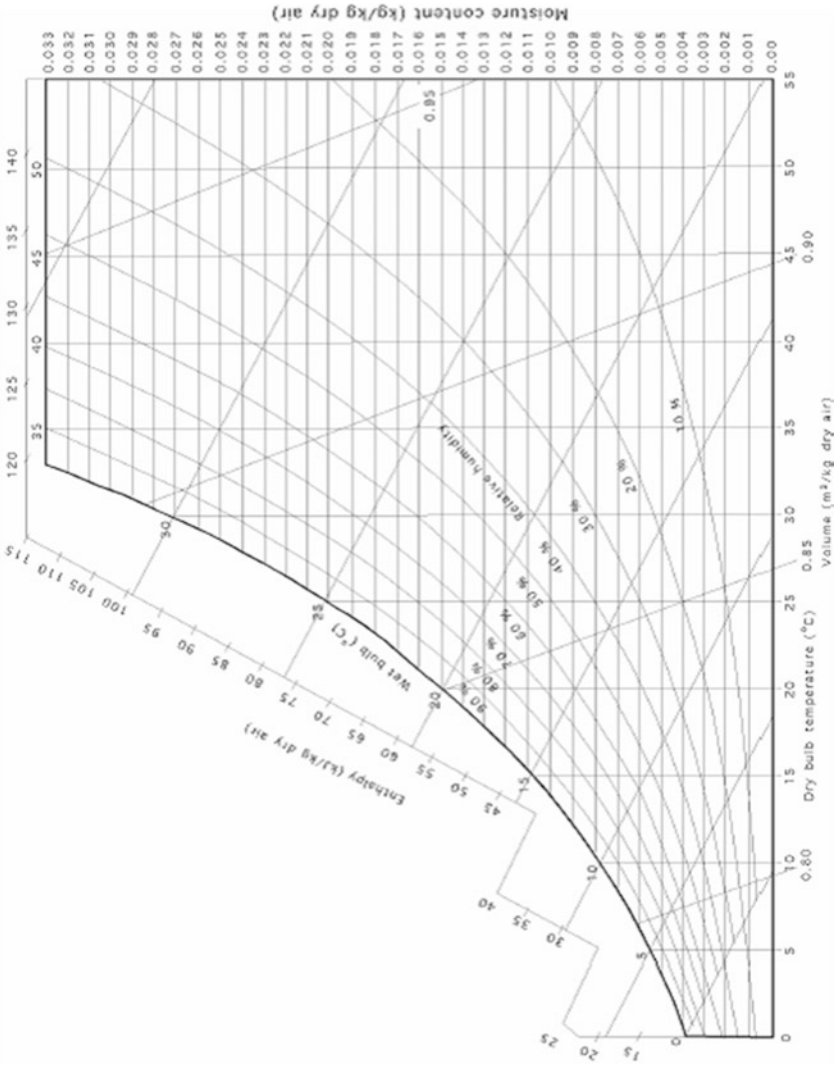

Fig. 23.11 Metric psychrometric chart

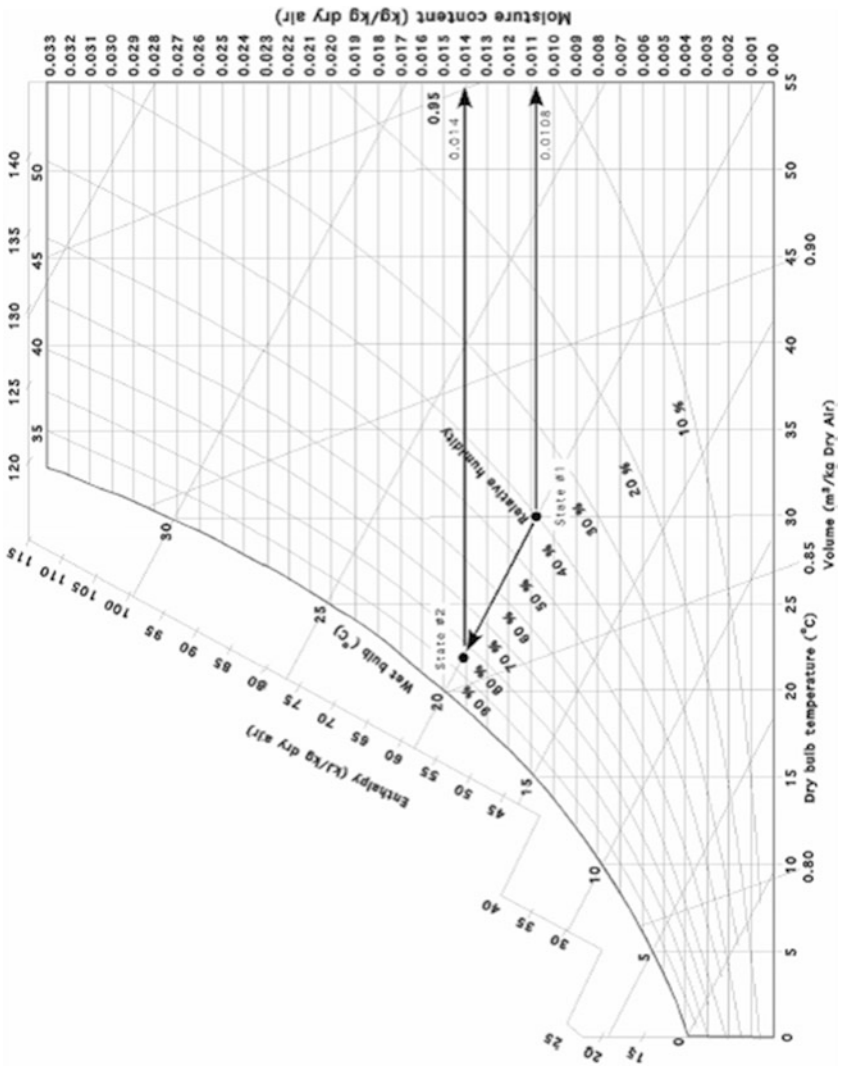

Fig. 23.12 Psychrometric chart for drying problem

Table 23.5 Information for drying problem

Properties	Initial	Final	Difference
Dry bulb (°C)	30°Cdb		
Wet bulb (°C)	20°Cwb		
Moisture (kg H_2O/kg of air)	0.0108	0.014	0.0032
Volume (m^3/kg dry air)	0.087		

from state point number 2. The result is a vector problem. The best estimate of the direction to move using the chart is to follow the wet-bulb line to the left and up until the second state point is reached, 90% relative humidity. In this example, evaporative cooling lowers the temperature from 100°Fdb to 81°Fdb, a difference of 19 F.

23.9 Metric Problems

Some of the SI units for psychrometrics are the same and some are different. Refer to Table 23.4 and Fig. 23.11 before attempting to complete a sample problem.

Problem Determine the size of fan (m^3/h) that will be required to naturally air dry 100.0 kg of product in 8.0 h. that must have 23.5 kg of water removed. The outside air conditions are 30°Cdb and 20°Cwb, and the air is 85% saturated when it leaves the dryer.

Solution Fans are sized by air moving capacity (m^3/h). The amount of air (m^3) is determined by the amount of water that must be removed and the amount of water that can be adsorbed by each cubic meter of air. The first step is to develop a table of pertinent information (Table 23.5 and Fig. 23.12).

$$\frac{\text{m}^3}{\text{h}} = \frac{23.5\ \text{kg H}_2\text{O}}{8.0\ \text{h}} \times \frac{1\ \text{kg air}}{0.0032\ \text{kg H}_2\text{O}} \times \frac{1\ \text{m}^3}{0.087\ \text{kg dry air}}$$

$$= \frac{23.5}{0.0022\ldots} = 10{,}551.36\ldots \quad \text{or} \quad 10{,}000\,\frac{\text{m}^3}{\text{h}}$$

Chapter 24
Selection of Structural Members

24.1 Objectives

1. Be able to understand the importance of beam size
2. Be able to define simple and cantilever beams
3. Be able to calculate the maximum load that can be carried by a beam
4. Be able to calculate the size of beam needed to support a load

24.2 Introduction

A beam is a horizontal member used to support a load. The design of structural members for a particular load involves analysis of the forces imposed on the member by loading and selection of appropriate materials, shapes, and sizes to accommodate the loads. This procedure is best accomplished by a structural engineer and is beyond the scope of this book. Failure to use a beam of adequate size can lead to beam failure with the accompanying danger of injury and/or financial loss. However several basic concepts are presented here to help the reader understand the properties and load-carrying abilities of simple and cantilever beams made of wood.

24.3 Simple and Cantilever Beams

Simple and cantilever beams are structural members that are loaded by forces applied at right angles to the longitudinal axis of the beam. The load that a beam can carry depends on its length, the method of support, the manner of loading, its cross-sectional size and shape, and the strength of the beam material.

Many types of beams and loads exist in buildings and structures, but only two types of beams and two types of loads are considered in this chapter. These are simple and cantilever beams and point and uniform loads. A simple beam is supported at

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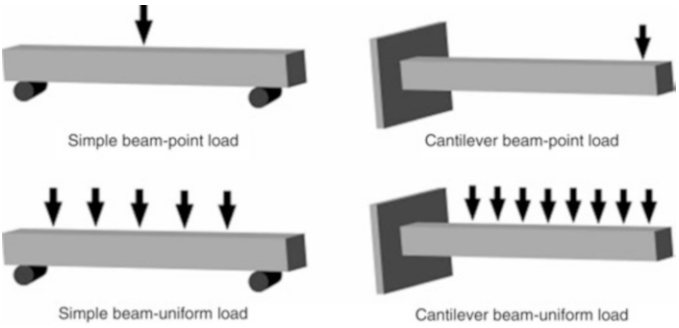

Fig. 24.1 Two types of beams and two types of loads

each end without rigid connections; it merely rests on supports. A cantilever beam is supported solidly at one end with the other end free to move (Fig. 24.1).

Point loads can be applied at any specific point along the beam, but the equations used in this chapter only apply to point loads in the middle of a simple beam and at the end of a cantilever beam. A single arrow indicates a point load. Uniform loads are applied along the entire length of the beam and are indicated by a series of arrows.

24.4 Beam Loading

When a load is applied to a simple beam, the beam tends to bend. As the beam bends or flexes, the fibers along the bottom surface of the beam are stretched (put in tension), and the fibers along the top surface of the beam are pressed together (compressed). It is important to remember that the opposite is true for a cantilever beam. The top of a cantilever beam stretches, and the bottom is compressed.

As the fibers of a beam stretch, a stress is generated in the fibers. When beam loading and fiber stretching proceed to a point where the fibers yield, the maximum allowable fiber stress (S) has been exceeded. Estimates for maximum allowable stress are available for most materials, and values for maximum allowable fiber stress of wood can be found in Appendix XI.

The shape of a beam and the way that it is positioned to carry a load greatly affect its load-carrying ability. The common sawing method for boards results in boards that are flat sawn; the grain of the wood tends to be parallel with the long dimension of the cross section (Fig. 24.2). A flat sawn beam will support more weight on edge than when placed flat.

The dimensions of a beam (width and depth) are used to determine the section modulus, which provides an index of the relative stiffness or load-carrying ability

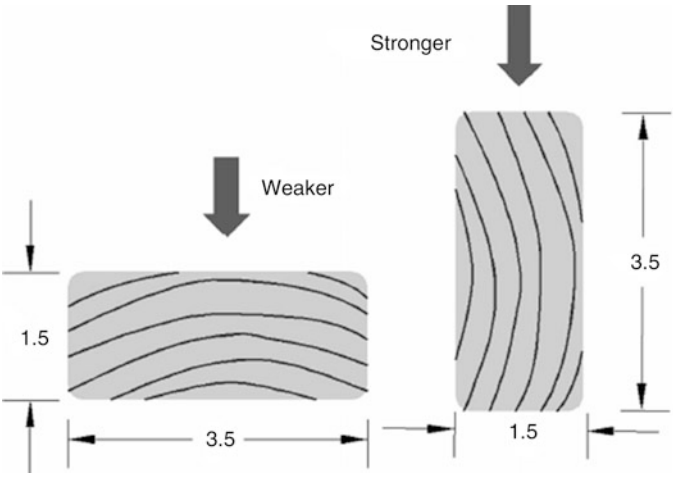

Fig. 24.2 Relative strength of lumber oriented with the shortest dimension parallel to the load (on its side) and the shortest dimension perpendicular to the load (on its edge)

of the member. For a rectangular cross-section member, the section modulus is determined by using the following equation:

$$K = \frac{1}{6} \times a \times b^2$$

where K = Section modulus, in^3; a = Width of member, horizontal dimension, in; b = Depth of member, vertical dimension, in.

24.5 Dimensioned Lumber

The lumber industry uses two different sizes, nominal size and actual size. The nominal size is the dimension of the lumber before it is sanded. The actual size is the size of the lumber after the surfaces have been finished. Finishing removes material; therefore the actual size is smaller than the nominal size (Table 24.1). Lumber is purchased using the nominal size, but the actual size must be used for beam calculations. An additional term may also be used and that is rough sawn or unfinished. When calculating beams using rough sawn or unfinished lumber, the actual size is the nominal size.

Problem What is the section modulus for a 2 × 4 wooden beam standing on edge?

Solution Section modulus is calculated on actual size. Therefore:

$$K = \frac{a \times b^2}{6} = \frac{1.5 \text{ in} \times (3.5 \text{ in})^2}{6} = 3.0625 \text{ or } 3.0 \text{ in}^3$$

To save time and eliminate one step in the calculations, Table 24.1 lists values for the section modulus of several common sizes of 2-inch (thick) lumber. Note that

Table 24.1 Section modulus of rectangular members

		Section modulus for position (in^3)	
		a b	a b
Nominal size (in)	Actual size (in)	On edge	Flat
2 × 2	1.50 × 1.50	0.56	0.56
2 × 3	1.5 × 2.50	1.56	0.94
2 × 4	1.5 × 3.50	3.06	1.31
2 × 6	1.5 × 5.50	7.56	2.06
2 × 8	1.5 × 7.25	13.14	2.72
2 × 10	1.5 × 9.25	21.39	3.47
2 × 12	1.5 × 11.25	31.64	4.22
2 × 14	1.5 × 13.25	43.89	4.97

in Table 24.1, the section modulus for a 2 × 4 on edge is 3.06. The nominal size (what one asks for at a lumber yard) and the actual size (the actual dimensions of the lumber) are shown. The section modulus is calculated for the actual size. Two columns of values are shown for the two possible positions of a member—standing on edge and lying flat. Notice that the values for the section modulus are much greater when the member is standing on edge, as it is much stiffer in this position.

The amount of weight that a beam can support is determined by the section modulus, allowable fiber stress, beam span or length, type of load, and type of support. For the two types of beams and loads being considered in this chapter, the following equations apply:

Simple beam, point load: $W = \dfrac{4SK}{L}$

Simple beam, uniform load: $W = \dfrac{8SK}{L}$

Cantilever beam, point load: $W = \dfrac{SK}{L}$

Cantilever beam, uniform load: $W = \dfrac{2SK}{L}$

where W = maximum allowable load on the beam, lb; S = allowable fiber stress, lb/in^2; L = length or span of beam, in; K = beam section modulus, in^3.

Problem What is the maximum point load that can be supported in the middle of a 4 × 6 inch, rough sawn simple beam 120 inches long when the allowable fiber stress is 1500 lb per square inch?

Solution

$$K = \frac{1}{6} \times a \times b^2 = \frac{1 \times 4 \text{ in} \times (6.0 \text{ in})^2}{6} = 24 \text{ in}^3$$

$$W = \frac{4SK}{L} = \frac{4 \times 1500 \dfrac{\text{lb}}{\text{in}^2} \times 24 \text{ in}^3}{120 \text{ in}} = 1200 \text{ lb}$$

24.6 Size of Beam

In the previous section, the method for determining the size of load that a beam will support was illustrated. In some situations it is necessary to determine the beam size that is necessary to support a given load. The same equations are used, but they are rearranged to solve for the section modulus. Once the section modulus is known, the beam size can be determined from Table 24.1 if one dimension is 2 inches (nominal) and the orientation is known.

Problem What is the smallest size of 2 inch, No. 1, southern pine simple beam that will support a uniform load of 2400 lb if the beam is 100 inches long?

Solution Using Table 24.1 and Appendix XI and rearranging the equation:

$$W = \frac{8SK}{L} \qquad K = \frac{W \times L}{8 \times S} = \frac{2400 \text{ lb} \times 100 \text{ in}}{8 \times 1000 \dfrac{\text{lb}}{\text{in}^2}} = 30 \text{ in}^3$$

Referring to Table 24.1 the smallest beam size with a section modulus equal to or larger than 30 cubic inches is a beam 2 inches wide and 12 inches deep. Notice that a 2 × 14 inch beam also would carry the load but is larger than necessary.

The procedures presented in the previous sections are not limited to boards 2 inches wide. If the section modulus and one dimension are known, the width of a beam greater than 2 inches can be determined if the equation is rearranged.

Problem What depth of board is needed in the previous problem if a board 4 inches wide is used?

Solution Rearranging the equation:

$$K = \frac{1}{6} \times a \times b^2 \qquad b = \sqrt{\frac{K \times 6}{a}} = \sqrt{\frac{30 \text{ in}^3 \times 6}{4 \text{ in}^2}} = \sqrt{45} = 6.708\ldots \text{ or } 6.7 \text{ in}$$

This example illustrates that a beam 4 × 6.7 inches (actual size) will support the same load as a beam 2 × 12 inches (nominal size).

24.7 SI Metric

The procedure to solve SI metric is the same as that for customary units. Lumber dimensions are often given in centimeters or millimeters. Stress is in kilopascals (kPa or kN/m^2). To convert from allowable stress in Appendix XI from psi (lb/in^2) to kPa, multiply $S_{\text{Customary}}$ by 6.8947 (Table 24.2).

Table 24.2 Metric lumber sizes

Nominal size (cm)	Actual size (cm)
5.0 × 5.0	4.5 × 4.5
7.5 × 5.0	7.0 × 4.5
10.0 × 5.0	9.0 × 4.5
15.0 × 5.0	14.0 × 4.5
10.0 × 10.0	9.0 × 9.0
10.0 × 15.0	9.0 × 14.0

Problem What is the maximum point load that can be supported in the middle of a 10 × 15 cm, rough sawn (dimensions are the *actual* dimensions of the board) simple beam on edge that is 3.0 m long? The board is No. 1 yellow pine.

Solution Allowable stress from Appendix XI is 1000 lb/in^2. Convert this value to SI units.

$$S_{\text{SI}} = 6.8947 \frac{\text{kPa}}{\text{lb}/\text{in}^2} \times S_{\text{Customary}}$$

$$S_{\text{SI}} = 6.8947 \frac{\text{kPa}}{\text{lb}/\text{in}^2} \times 1{,}000\,\text{lb}/\text{in}^2 = 6894.7\text{kPa}$$

$$K = \frac{1}{6} \times a \times b^2 = \frac{1 \text{ x } 10 \text{ cm x } (15.0 \text{ cm})^2 \times \frac{1 \text{ m}}{100 \text{ cm}} \times \left(\frac{1 \text{ m}^2}{10{,}000 \text{ cm}^2}\right)}{6}$$

$$= \frac{0.00225}{6} = 0.000375 \text{ m}^3$$

$$W = \frac{4SK}{L} = \frac{4 \text{ x } 6{,}894.7 \frac{\text{kN}}{\text{m}^2} \times 0.000375 \text{ m}^3}{120 \text{ in} \times 0.0254 \frac{\text{m}}{\text{in}}}$$

$$= \frac{10.34205 \text{ kN-m}}{3.048 \text{ m}} = 3.39306 \text{ or } 3.39 \text{ kN}$$

Problem Determine the maximum load that can be supported on the end of a finished 100 mm × 50 mm cantilever beam that is 4.0 m long. The beam is on edge and is No. 2 southern pine.

Solution Converting allowable stress:

$$S_{\text{SI}} = 6.8947 \frac{\text{kPa}}{\text{lb}/\text{in}^2} \times S_{\text{Customary}}$$

$$= 6.8947 \frac{\text{kPa}}{\text{lb}/\text{in}^2} \times 825 \frac{\text{lb}}{\text{in}^2}$$

$$= 5{,}688.1275 \text{ kPa}$$

solving for K:

$$\begin{aligned} K &= \frac{1}{6} \times a \times b^2 \\ &= \frac{1 \times 4.5 \text{ cm} \times (9.0 \text{ cm})^2 \times \dfrac{1 \text{ m}}{100 \text{ cm}} \times \dfrac{1 \text{ m}^2}{10{,}000 \text{ cm}^2}}{6} \\ &= 6.075 \text{ E-5 m}^3 \end{aligned}$$

solving for W:

$$\begin{aligned} W &= \frac{SK}{L} = \frac{5688.1275 \text{ kPa} \times 6.075 \text{ E-5 m}^3}{4.0 \text{ m}} \\ &= \frac{0.3455\ldots}{4} = 0.086388\ldots \text{ or } 0.09 \text{ kN} \end{aligned}$$

Chapter 25
Principles of Electricity

25.1 Objectives

1. Be able to define electricity
2. Be able to define basic electrical terms
3. Be able to understand and use Ohm's law
4. Be able to calculate electrical power
5. Be able to calculate electrical energy use

25.2 Introduction

Agricultural production depends heavily upon electrical energy to power machines, lights, equipment, and tools used in producing and processing agricultural products. An understanding of the principles of electricity will lead to a more efficient use of electricity and reduce the risks associated with working around electricity.

25.3 Electricity

Electricity is the flow of electrons from one atom to another. Scientists believe that electricity was first noted when ancient people discovered the attraction between an amber rod and other materials.

An understanding of electricity begins with the atom. Electrons travel in orbit around a nucleus composed of protons and neutrons. When an atom has the same number of protons and electrons, it has no charge. When it has more electrons than protons, it has a negative charge, and if more protons than electrons, a positive charge. As electrons move from one atom to another, electric current is produced.

A flow of electrons can be produced by different methods, including friction, heat, light, pressure, chemical action, and magnetism. The last two are used most often in agriculture.

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25.4 Electrical Terms

To understand electricity and how it functions, it is important to understand common electrical terms and their definitions.

Current:	Current is the movement of electrons through a conductor. The amount of current moving is determined by the voltage divided by the resistance.
Alternating current (AC):	One of the two types of electric current; alternating current does not exhibit constant polarity or a constant voltage. The voltage builds to a maximum value in one polarity, declines to zero, builds to a maximum value in the other polarity, and declines to zero again, Fig. 25.1. This sequence is called one cycle. In the United States, the common current is 60 cycle; that is, 60 complete cycles occur every second.
Direct current (DC):	This current flows in one direction only and at a constant voltage, Fig. 25.2. The polarity will be either positive or negative.
Amperage (amp):	A unit of measure for the amount of electricity flowing in a circuit. One ampere of current is equivalent to 6.28×10^{18} electrons per second.
Circuit:	A continuous path for electricity from the source to the load (machine or appliance using the electricity) and back to the source.
Conductor:	Any material that has a relatively low resistance to the flow of electricity. Such materials allow electrons to flow easily from one atom to another. Most metals are good conductors.
Insulator:	Any material that has a relatively high resistance to the flow of electricity. Such materials do not allow easy movement of electrons from one atom to another. Glass, rubber, and many plastics are insulators.
Resistance (Ohm):	The characteristic of materials that impedes the flow of electricity. All materials have varying amounts of electrical

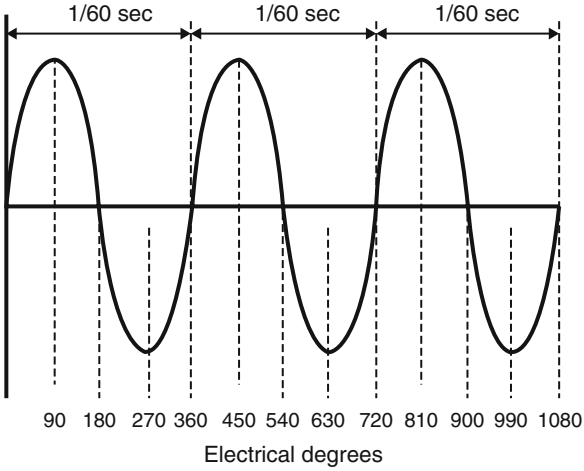

Fig. 25.1 Three complete cycles of 60 cycle alternating current

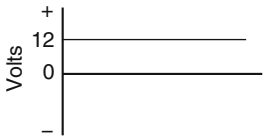

Fig. 25.2 Direct current at positive 12 V

resistance. Two characteristics of resistance are important: (1) when electricity flows through a resistant material, heat is generated and (2) when electricity flows through a resistant material, the voltage is decreased. Resistance is measured in units of ohms and designated by the Greek letter Ω (omega).

Voltage (V) : The electromotive force that causes electrons to flow through a conductor. Voltage is a measure of the potential for current flow. A voltage potential may exist between objects without a flow of current. In the United States, the two standard voltages are nominally 120 V and 240 V.

Watts (W): Unit of electrical power. Watts are determined by multiplying the voltage times the amperage.

Ohm's law: Ohm's law explains the relationship between current, voltage, and resistance. Ohm's law states that the voltage in a circuit is equal to the amperage times the resistance. Expressed as an equation:

$$E = IR$$

where E = Voltage, V; I = Current, amp; R = Resistance, ohms.

It is common to rearrange this equation to solve for any one of the three variables. For example:

$$I = \frac{E}{R} \quad \text{and} \quad R = \frac{E}{I}$$

Problem What is the current flow (amp) when the source supplies 120 V and the circuit has 20.0 ohms (Ω) of resistance?

Solution

$$I = \frac{E}{R} = \frac{120\ \text{V}}{20.0\ \Omega} = 6.0\ \text{amp}$$

25.5 Electrical Power

By definition power is the rate of doing work. In electricity work is done by electrons moving within a conductor and is the result of the electrical potential (V) and the flow rate of the electrons (amp). Thus, in an electrical circuit, power is the product of volts × amperes. The basic units of electrical power are the watt (W) and the kilowatt (kW). In equation form:

$$P = E \times I$$

where P = power, watts; E = voltage, V; I = current, amp.

Problem How much power, W, is being produced when a current is measured at 5.0 amps and 120.0 V?

Solution

$$P = E \times I = 120 \text{ V} \times 5.0 \text{ amp} = 600 \text{ watt}$$

Power also may be expressed in two other ways. Ohm's law states that $E = I \times R$ and (power) $P = E \times I$; therefore the E in the power equation can be replaced with IR from Ohm's law:

$$P = IR \times I \quad \text{or} \quad P = I^2R$$

Ohm's law also states that $I = \frac{E}{R}$; therefore:

$$P = E \times \frac{E}{R} \quad \text{or} \quad P = \frac{E^2}{R}$$

Note that the use of either of these equations requires knowledge of a value for the resistance. When the resistance and one of the other quantities are known, power can be determined.

25.6 Electrical Energy

Electrical energy is different from electrical power because it includes the element of time. The amount of electrical energy produced, or used, is determined by multiplying the electrical power (watts) by the amount of time electricity flows (hours). The result is expressed in the units for electrical energy, watt-hours (Wh). For many uses of electricity, energy use measured in watt-hours is a large number. The electric industry has adopted a more convenient unit, the kilowatt-hour (kWh), as the basic unit of electrical energy. One kilowatt equals 1000 W. The amount of electrical energy used can be determined by:

$$\text{EE (Wh)} = P \times T$$

and:

$$\text{EE (kWh)} = P \times T \times \frac{1 \text{ kWh}}{1000 \text{ Wh}}$$

where EE = Electrical energy, Wh; P = Power, W; T = Time, hr.

Problem How much energy (Wh) is required to operate a 150 W light bulb for 3.5 h?

Solution

$$\text{EE} = P \times T = 150 \text{ W} \times 3.5 \text{ hr} = 525 \text{ Wh}$$

Expressed in kW h:

$$\text{kWh} = 525\ \text{Wh} \times \frac{1\ \text{kW}}{1000\ \text{W}} = 0.525\ \text{kW h}$$

Electrical energy also is used to determine the cost of using electricity. It is common practice for an electric utility company to sell electricity on a cent (¢) per kilowatt-hour basis. When the electric rate (¢/kWh) and the amount of electricity (kWh) are known, the cost of operating any electrical appliance or motor can be determined. In the following example, the unit cancellation method is used.

Problem What will it cost to operate the light bulb in the previous problem? The electricity cost is 10 ¢/kWh.

Solution Using unit cancellation:

$$\text{Cost (cents)} = 0.525\ \text{kWh} \times \frac{10\ \text{cents}}{\text{kW h}} = 5.25 \text{ or } 5.2\ \text{cents}$$

When the electricity costs 10 ¢/kWh, it will cost 5.2 cents to operate a 150 W light bulb for 3.5 h.

25.7 SI Metric Customary Calculations

It is obvious from the examples that electrical calculations are performed in SI units. If the unit of power is horsepower, use the conversion constant 1 hp = 0.743 kW and work the problem in SI units.

Chapter 26
Series and Parallel Circuits

26.1 Objectives

1. Be able to identify series and parallel circuits
2. Be able to determine the total resistance of both series and parallel circuits
3. Be able to attach a voltmeter and an ammeter correctly
4. Be able to determine the amperage and the voltage at any point within a series or a parallel circuit
5. Be able to explain the importance of system and equipment grounding

26.2 Introduction

The purpose of electrical circuits is to supply electricity for appliances, tools, and other electrical devices. These devices are called loads. Before the load will operate, electricity must have a complete path from the source to the load and back to the source. This path for electricity is called a circuit. Two types of circuits are used to supply electrical power for agricultural loads, series, and parallel.

This chapter will explore some of the principles of series and parallel circuits and how to calculate the amperage and/or voltage of these circuits.

26.3 Series and Parallel Circuits

The following discussion will explain the differences between the two circuits and how to calculate the total resistance of the circuit. *Note*: to aid in the understanding of the following discussion of circuits, assume that the conductors in the circuit have no resistance.

26.3.1 Series Circuit

In a series circuit, the electricity has no alternative paths. All of the electricity must pass through all of the components in the circuit (Fig. 26.1).

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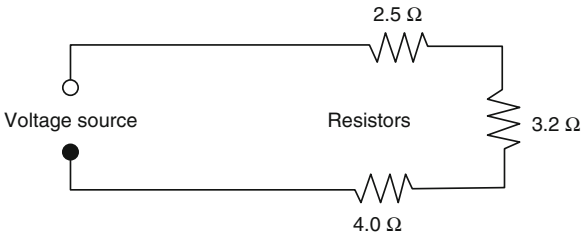

Fig. 26.1 Series circuit

For the electricity to leave and return to the source, it must pass through all three loads, resistors. In a series circuit, the total resistance of the circuit is the sum of each resistance:

$$R_T = R_1 + R_2 + R_3 + \ldots + R_N$$

The total resistance of the circuit in Fig. 26.1 is:

$$R_T = 2.5\,\Omega + 3.2\,\Omega + 4.0\,\Omega = 9.7\,\Omega$$

The total amperage flow in the circuit can be determined by dividing the source voltage by the total resistance.

Problem What is the current flow for the circuit in Fig. 26.1 when the source voltage is 120 V?

Solution

$$E = IR \quad I = \frac{E}{R} \quad I = \frac{120\,\text{V}}{9.7\,\Omega} = 12.3711\ldots \text{ or } 12\,\text{A}$$

26.3.2 Parallel Circuit

In a parallel circuit, the electricity has alternative paths to follow (Fig. 26.2).

The total resistance of a parallel circuit is less than the sum of the individual resistances. The current flow at the source is determined by the total resistance, but total resistance is determined differently from series circuits. The amperage through any path is determined by the voltage at the path and the resistance of the path.

The total resistance can be determined by more than one method. In the first method, the inverse of the total resistance is the sum of the inverses of each resistance in the parallel circuit:

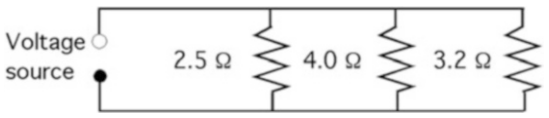

Fig. 26.2 Parallel circuit

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_N}$$

This method requires adding fractions, which requires solving for a common denominator or reducing the fractions to a decimal. The easiest way to determine a common denominator is to multiply the denominators. When this method is used for the circuit in Fig. 26.2, the total resistance is:

$$\begin{aligned}\frac{1}{R_T} &= \frac{1}{2.5\,\Omega} + \frac{1}{4.0\,\Omega} + \frac{1}{3.2\,\Omega} \\ &= \frac{12.8}{32} + \frac{8}{32} + \frac{10}{32} \\ &= \frac{30.8}{32} = 0.9625 \\ R_T &= \frac{1}{0.9625} = 1.039\ldots \text{ or } 1.0\,\Omega\end{aligned}$$

Using this method the inverse of the total resistance is 0.96 Ω and the resistance is 1.0 Ω.

Problem Determine the total resistance of the parallel circuit in Fig. 26.2 by reducing the fractions to decimals.

Solution

$$\begin{aligned}\frac{1}{R_T} &= \frac{1}{2.5\,\Omega} + \frac{1}{4.0\,\Omega} + \frac{1}{3.2\,\Omega} \\ &= 0.4 + 0.25 + 0.3125 \\ &= \frac{1}{0.9625} = 1.038\ldots \text{ or } 1.0\,\Omega\end{aligned}$$

Compare the total resistance of this circuit to the total resistance of the series circuit. With the same resistors, the total resistance is much less in a parallel circuit.

A third method is to solve for the equivalent resistance of pairs of resistors until all of the resistance in the circuit is reduced to a single resistance. This is accomplished by using the equation:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

When the circuit has more than two resistors, determine the equivalent resistance (R_E) for any two, and then combine it with the third and so on until only a single resistance remains. The circuit resistance of the circuit in Fig. 26.2 with this method is:

$$\begin{aligned}R_E &= \frac{2.5\,\Omega \times 4.0\,\Omega}{2.5\,\Omega + 4.0\,\Omega} = \frac{10\,\Omega}{6.5\,\Omega} = 1.538\ldots\ \Omega \\ R_T &= \frac{1.538\ldots\ \Omega \times 3.2\,\Omega}{1.538\ldots\ \Omega + 3.2\,\Omega} = \frac{4.92\ldots}{4.738\ldots} = 1.038\ldots \text{ or } 1.0\,\Omega\end{aligned}$$

Using this method the total resistance is 1.0 Ω, which agrees with the other two methods.

26.4 Series–Parallel Circuits

A series–parallel circuit combines characteristics of both types of circuits. Some of the resistors are in series and some are in parallel. This type of circuit is more common in electronic equipment than in the circuits used to supply electrical power for agricultural equipment (Fig. 26.3).

Study Fig. 26.3. In circuit A all of the electricity must pass through the 2.5 Ω resistor, but then it has alternative paths. Part of the current will pass through the 4.0 Ω resistor, and the rest will pass through the 3.2 Ω resistor. Circuit B is the same circuit just drawn differently so that it is easier to see the relationship between the three resistors.

To solve for the total resistance of a series, parallel circuit, start by reducing the parallel resistors. The parallel resistors can be reduced to the equivalent resistance using any one of the three methods discussed in Sect. 26.3.2. The circuit then acts as a series circuit and the resistances can be added.

It is helpful to redraw the circuit after each pair of parallel resistors is condensed. To determine the total resistance for Fig. 26.3, the first step is to find the equivalent resistance of the parallel branch of the circuit. Either parallel circuit equation can be used.

$$R_E = \frac{4.0\,\Omega \times 3.2\,\Omega}{4.0\,\Omega + 3.2\,\Omega} = \frac{12.8\,\Omega}{7.2\,\Omega} = 1.777\ldots\ \Omega$$

The resistance of the parallel branch of the circuit has an equivalent resistance of 1.777... Ω. The next step is to combine this equivalent resistance with the remaining resistors in the circuit.

Figure 26.4 shows that the series–parallel circuit can be reduced to a series circuit. The total resistance of this circuit is:

$$R_T = 2.5\,\Omega + 1.777\ldots\ \Omega = 4.277\ldots\ \Omega \text{ or } 4.3\,\Omega$$

The series–parallel circuit has a total resistance of 4.3 Ω.

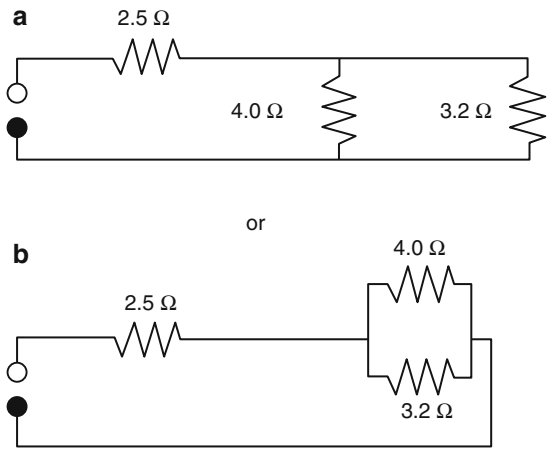

Fig. 26.3 Two representations of a series—parallel circuit

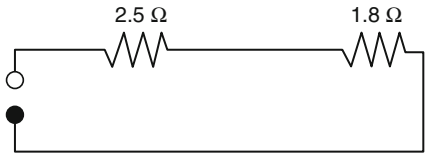

Fig. 26.4 Equivalent series resistance of Fig. 26.3

26.5 Determining Voltage and Amperage in Circuits

In agricultural circuits the voltage is determined by the source of the electrical energy. Standard domestic service is 120 or 240 V. Some stationary equipment with large power demands will require 440 volts. Any agricultural equipment that uses a battery will operate on 6, 12, 24, or 48 V.

Amperage is determined by measuring the circuit with an ammeter or by calculations using Ohm's law:

$$E = IR$$

where E = electromotive force, V; I = intensity, amp; R = resistance, ohms.

Ohms law has three variables. If any two are known, the equation can be rearranged to solve for the third. The total amperage of a circuit can be calculated by dividing the source voltage by the total resistance of the circuit. Rearranging Ohm's law for amperage:

$$I = \frac{E}{R}$$

Problem Determine the total amperage for the series circuit illustrated in Fig. 26.5. Use 120 V for the source.

Solution Using Ohm's Law:

$$I = \frac{E}{R} = \frac{120\,\text{V}}{2.5\,\Omega + 3.2\,\Omega + 4.0\,\Omega} = \frac{120\,\text{V}}{9.7\,\Omega} = 12.371\ldots \text{ or } 12\,\text{amp}$$

A circuit with 9.7 Ω of resistance and a source voltage of 120 V will have a current flow of 12 amps.

The same procedure is used to determine the amperage of a parallel circuit. The source voltage is divided by the total resistance in the circuit.

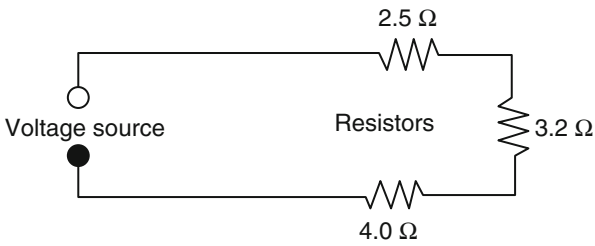

Fig. 26.5 Series circuit for sample problem

26.6 Using Voltmeters and Ammeters

It is helpful when troubleshooting circuits to be able to measure the voltage and amperage in the circuit. The instruments used for this purpose are called voltmeters and ammeters. When attached properly they will measure the voltage and amperage in a circuit.

26.6.1 Voltmeters

Two characteristics of circuits must be remembered in using voltmeters: (1) Voltage is the measurement of a potential between two points; so the reading on a voltmeter is the difference between the connection points. To reduce the effect of adding a voltmeter to the circuit, a meter is constructed with a very high internal resistance. (2) Anytime electricity flows through a resistance, heat is produced. Heat is energy loss from the circuit. The loss of energy causes the voltage to decrease. This decrease is called the voltage drop.

26.6.1.1 Voltmeters in Series Circuits

In Fig. 26.6 voltmeter number one (V_1) is connected across the source; therefore the reading on the voltmeter will be equal to the source, assuming no resistance in the conductors.

Voltmeter number two (V_2) is connected across the 3.2 Ω resistor. It will measure the difference in voltage from one side of the resistor to the other—in other words, the voltage drop across the resistor.

Problem What will voltmeter number 2 read in Fig. 26.6 if the source voltage, measured by voltmeter number 1, is 120 V?

Solution Voltmeter number 2 is measuring the voltage drop caused by the 3.2 Ω resistor. To calculate the voltage drop across the resistor, the total current flow in the circuit must be known. The first step is to calculate the total current flow in the circuit. To calculate total current flow, the total resistance must be known.

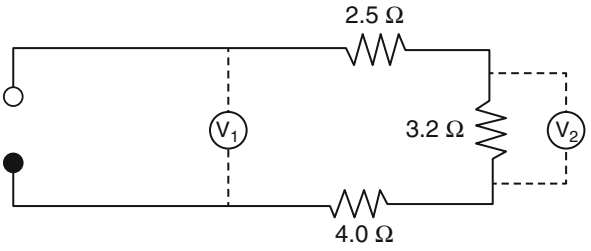

Fig. 26.6 Voltmeters in series circuit

$$
\begin{aligned}
R_T &= R_1 + R_2 + R_3 \\
&= 2.5\,\Omega + 3.2\,\Omega + 4.0\,\Omega \\
&= 9.7\,\Omega \\
E = IR \quad I &= \frac{E}{R} = \frac{120\,\text{V}}{9.7\,\Omega} = 12.37\ldots A
\end{aligned}
$$

The next step is to determine the voltage drop across the resistor:

$$E = IR = 12.37\ldots \text{ amp} \times 3.2\,\Omega = 39.58\ldots \text{ or } 40\,\text{V}$$

When 12 amps flow through a resistance of 3.2 Ω with a source of 120 V, there is a voltage drop of 40 V. Voltmeter 2 will have a reading of 40 V.

26.6.1.2 Voltmeters in Parallel Circuits

In a parallel circuit, voltmeters connected across the resistors are, in essence, connected across the source voltage. Therefore, assuming that there is no voltage drop from the resistance of the wire, both voltmeters in Fig. 26.7 will have the same reading as the source voltage.

26.6.2 Ammeters

Ammeters are used to measure the amount of current flowing in a circuit. The laboratory type of ammeter is connected in series. To reduce the effect of the meter on the performance of the circuit, they are constructed with a very low resistance. A clamp-on type of meter is also available that measures the intensity of the electromagnetic field around a single conductor and converts the field intensity into amperage.

26.6.2.1 Ammeters in Series Circuits

When the amperage was calculated in the circuit in Fig. 26.6, it was determined that with a 120 V source the current was 12 amps. In a series circuit, the electricity does not have alternative paths to follow. Because all of the amperage flows through all components in the circuit, both ammeters in Fig. 26.8 will have a reading of 12 amps.

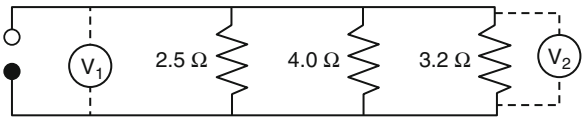

Fig. 26.7 Voltmeters in parallel circuits

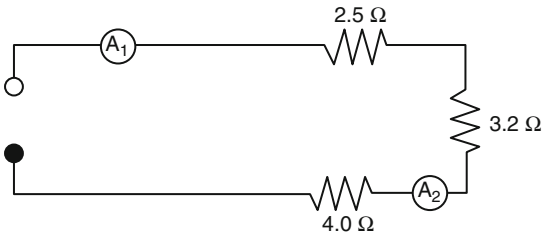

Fig. 26.8 Ammeters in a series circuit

26.6.2.2 Ammeters in Parallel Circuits

In parallel circuits ammeters must also be attached in series; but because the electricity has alternative paths, they will only measure the current in the conductor they are inserted into; see Fig. 26.9.

Problem What are the readings for ammeters 1 and 2 in Fig. 26.9 when the source voltage is 120 V?

Solution In this example problem, ammeter one is located between the source and the first branch on the circuit; therefore it will measure the total current flow in the circuit. Ammeter two is in the last branch of the circuit; therefore it will only measure the current flowing through that branch on the circuit. In a previous section, it was explained that to measure current flow, the source voltage and the total resistance of the circuit must be known. The first step in determining the readings of the amp meters is to determine the total resistance of the circuit:

$$\begin{aligned}\frac{1}{R_T} &= \frac{1}{2.5\,\Omega} + \frac{1}{4.0\,\Omega} + \frac{1}{3.2\,\Omega} \\ &= \frac{12.8}{32} + \frac{8}{32} + \frac{10}{32} \\ &= \frac{30.8}{32} = 0.9625 \\ R_T &= \frac{1}{0.9625} = 1.038\ldots\ \Omega\end{aligned}$$

The next step is to calculate the total current flow in the circuit:

$$E = IR\,I = \frac{E}{R} = \frac{120\,\text{V}}{1.038\ldots\Omega} = 115.5 \text{ or } 120 \text{ amps}$$

Ammeter number 1 will have a reading of 120 amps.

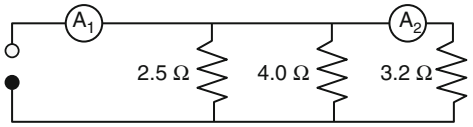

Fig. 26.9 Ammeters in a parallel circuit

Ammeter number 2 only will measure the current flow in that branch of the circuit. Ohm's law is used to solve this part of the problem also:

$$E = IR \quad I = \frac{E}{R} = \frac{120\,\text{V}}{3.2\,\Omega} = 37.5 \text{ or } 38 \text{ amps}$$

In summary, assuming no resistance in the conductors, in a series circuit, the amperage remains the same, and the voltage changes as the resistance changes. In parallel circuits the voltage remains the same, and the amperage changes as the resistance changes in the circuit.

26.7 Grounding

To simplify the earlier discussion of circuits, only two conductors were used, the hot and neutral. Current wiring codes require at least three conductors: hot, neutral, and ground. The ground conductor is attached to the case of metal-cased tools and some metal electrical components. The purpose of the ground conductor to provide a low resistance circuit to the earth (Fig. 26.10).

This is accomplished for metal-cased tools by attaching the grounding conductor to the case of the tool and the grounding bar in the service entrance panel. If a short occurs between the electrical components and the case or frame of the metal tool, the low-resistance ground circuit will permit a current flow greater than the circuit overcurrent protection (fuse or circuit breaker), causing the circuit to open. If a short occurs and the ground circuit is not continuous from the case or frame of the tool to the earth, the operator's body or body parts may complete the circuit resulting in a potentially fatal electric shock.

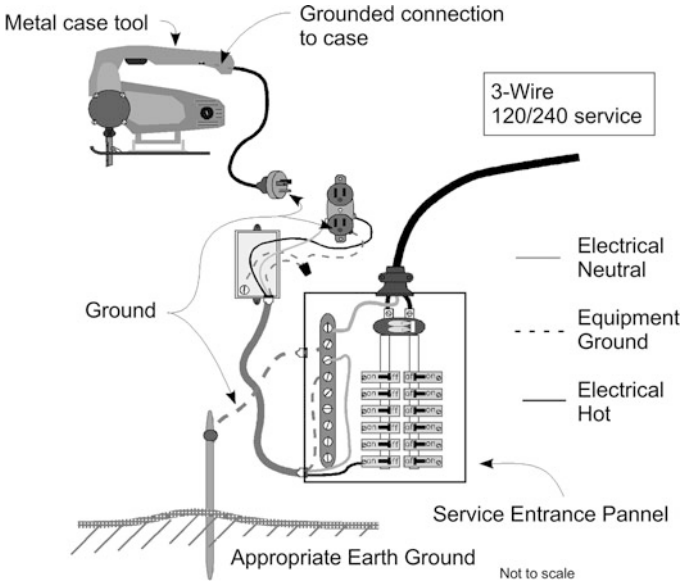

Fig. 26.10 Case of equipment ground

Chapter 27
Sizing Conductors

27.1 Objectives

1. Understand the importance of using electrical conductors of the proper size.
2. Be able to calculate voltage drop.
3. Be able to calculate the proper size conductor.
4. Be able to select the proper size conductor from a table.
5. Understand the importance of circuit protection, and be able to identify the three common types.

27.2 Introduction

Conductors are used to provide a path for electricity. The metals used for conductors have a low resistance, but electricity passing through any resistance causes heat, which results in a voltage drop. Increasing the current flow will increase the heat produced. Heating the conductors above their designed operating temperatures will cause the insulation to fail, which can lead to shorts. The heat generated can be sufficient to start a fire if flammable materials are close. To prevent overheating the conductors, voltage drop is used to size conductors.

27.3 Calculating Voltage Drop

Allowable voltage drop in conductors is determined by standards. The primary standard in the United States is the National Electric Code. For most circuits this is 2% or 3%. Voltage drop occurs because materials resist the flow of electricity; the critical issue is to ensure it does not become excessive. The amount of voltage drop is determined by the amount of current and the total resistance in the circuit. The size of a conductor required for an electrical load is determined by the allowable voltage drop for the circuit, the size of the load, and the length of wire from the source of electricity to the load. The resistance of conductors usually is listed as ohms (Ω) per

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H.L. Field, J.M. Long, *Introduction to Agricultural Engineering Technology*,
https://doi.org/10.1007/978-3-319-69679-9_27

1000 ft of conductor length. Because the electricity must pass through the entire length of a conductor, conductors perform as one continuous series resistance.

Appendix XII includes the resistance for various sizes of copper wire using AWG sizes, and Appendix XIII lists the resistance values for SI wire sizes. Notice that the resistance is given in ohms/1000 ft or ohms/100 m. Bare wire is seldom used in circuits, but because the type of insulation used influences the resistance, these values are used to illustrate the principles of voltage drop. Resistance values for wires with different types of insulation can be found in the *National Electrical Code* (NEC) or other sources, and these must be used when calculating wire size for a specific application.

The voltage drop is calculated using Ohm's law. For general purpose circuits, the voltage drop must be limited to 2%. The NEC allows a 3% drop for some individual circuits. In calculating voltage drop, the length of conductor usually will be measured as either the length of wire from the source to the load and back (length of wire) or the run (the distance from the source to the load).

Problem What is the voltage drop for a wire with a length of 1500.0 ft when No. 12 wire is used and the load is 10.0 amps?

Solution Using Ohm's law and, from Appendix XII, using a resistance for No. 12 wire of 1.62 Ω/1000 ft the voltage drop is:

$$E = IR = 10.0\,\text{amp} \times \frac{1.62\ \Omega}{1000.0\ \text{ft}} \times 1500.0\,\text{ft} = \frac{24{,}300}{1000.0} = 24.3\,\text{V}$$

The 1500.0 feet of No. 12 wire has a voltage drop of 24.3 V. Is this an acceptable voltage drop if the source voltage is 120 V?

$$\% = \frac{24.3\text{V}}{120\,\text{V}} \times 100 = 20.25\%$$

The answer is no. A 20.25% voltage drop is excessive. If 1500 feet of No. 12 wire is used with this load, the electrical appliance will not operate correctly, the conductors will overheat, and there is the potential for a fire. A larger conductor size is needed to carry a load of 10.0 amps for a distance of 1500.0 feet.

For wires longer or shorter than 1000 feet, the resistance is proportional to the length. The total resistance for any length is:

$$R_\text{L} = \frac{R(\Omega)}{1000\,\text{ft}} \times L(\text{ft})$$

where R_L = Resistance in ohms (Ω) for any length, ft; R = Resistance per 1000 ft, Ω; L = Length of wire, ft.

27.4 Calculating Conductor Size

The previous problem was used to illustrate the principle of voltage drop. In practice because the percent of drop is fixed by electrical codes, conductors are sized by calculating the amount of resistance per 1000 feet that will result in an

acceptable voltage drop and then selecting the appropriate size of wire from a table similar to Appendix XII.

Problem What size of wire is needed to carry a 120 V, 15.0 amp load with a 2% drop when the run is 200.0 ft?

Solution The first step is to determine the permissible amount of voltage drop:

$$\text{Voltage drop}(V_D) = 120\,\text{V} \times 0.02 = 2.4\,\text{V}$$

The second step is to determine the amount of resistance for the load that will cause a 2.4 V drop. This is accomplished using Ohm's law:

$$E = IR \qquad R = \frac{E}{I} = \frac{2.4\,\text{V}}{15.0\,\text{amp}} = 0.16\,\Omega$$

For a circuit with a resistance of less than 0.16 Ω and a load of 15.0 amps, the voltage drop will be less than 2%. Remember that the voltage used to calculate the resistance is the voltage drop not the source voltage.

To select the correct size of wire, the calculated circuit resistance must be converted to units of Ω/1000 feet and then select the appropriate wire size from Appendix XII. This can be accomplished using unit cancellation:

$$\begin{aligned}\frac{\Omega}{1000\,\text{ft}} &= \frac{\Omega}{\text{Run}} \times 1000\,\text{ft} \\ &= \frac{0.16\,\Omega}{2 \times 200.0\,\text{ft}} \times 1000\,\text{ft} = 0.40\frac{\Omega}{1000\,\text{ft}}\end{aligned}$$

Next, compare this value to the resistance values in Appendix XII. The objective is to select a size of wire with a resistance equal to or less than the calculated value. From Appendix XII, the resistance of No. 6 wire is 0.41 Ω/1000 feet, and the resistance of No. 4 wire is 0.26 Ω/1000 feet. The No. 4 wire would be the best choice as the resistance is closest to the calculated resistance without being larger.

These examples illustrate the principle that voltage drop is caused by resistance and current. Another example of the importance of understanding voltage drop is in the use of extension cords. Improper use of extension cords can lead to serious consequences. Many extension cords sold in retail stores use No. 16 or No. 18 wire. Extension cords of this size are very limited in current carrying capacity. In addition when more than one extension cord is used, the resistance of the connection can be equal or greater than the resistance of the wire. If the connections of an extension cord that has been used for a while are warm, the extension cord is overloaded.

Problem What size load (amp) can a 100.0 ft, No. 18 extension cord carry on a 120 V circuit without exceeding a 2% voltage drop?

Solution The first step is to determine the allowable voltage drop:

$$V_D = 120\,\text{V} \times 0.02 = 2.4\,\text{V}$$

The next step is to determine the amount of current that will cause a 2.4 V drop in the extension cord. This is accomplished by using Ohm's law and the resistance of

No. 18 wire. Remember to use two times the length (100.0 ft × 2 = 200.0 ft) to determine the total feet of conductor:

$$E = IR \qquad I = \frac{E}{R} = \frac{2.4\,\text{V}}{\frac{6.51\,\Omega}{1000\,\text{ft}} \times 200.0\,\text{ft}} = \frac{2.4\,\text{V}}{1.302\,\Omega} = 1.843\ldots \text{ or } 1.84\,\text{amp}$$

The maximum electrical load for a 100 ft, No. 18 extension cord is 1.84 amps. If the extension cord is used for a larger load (more amps) it will overheat.

An often unrecognized factor when using extension cords is the resistance of the connections. Two 50 ft extension cords attached together will have more resistance than a single 100 foot cord with the same size of conductors. Consider the following example that presents this potential problem with extension cords.

Problem What is the maximum capacity of the No. 18 extension cord in the previous problem if two 50 ft cords are used, and the connection has a resistance of 8.0 Ω?

Solution Using an allowable voltage drop of 2.4 V and Ohm's law:

$$E = IR \qquad I = \frac{E}{R} = \frac{2.4\,\text{V}}{\left(\frac{6.51\,\Omega}{1000\,\text{ft}} \times 200.0\,\text{ft}\right) + 8.0\,\Omega}$$

$$= \frac{2.4\,\text{V}}{1.302\,\Omega} = 0.2580\ldots \text{ or } 0.26\,\text{amp}$$

This example shows that using two 50 foot extension cords instead of one 100 foot cord reduces the capacity by seven times when the connection resistance is 8.0 ohms because of the additional resistance of the connection.

Many appliances are rated in watts. To determine the size of conductors required to supply an appliance rated in watts, the electrical power (watts) must be used first to determine the load in amps.

Problem A 25.0 ft extension cord will be used to operate a 1100 W, 120 V electrical iron. What size of extension cord should be selected?

Solution The first step is to determine the amperage used by the iron:

$$P = EI \quad I = \frac{P}{E} = \frac{1100\,\text{W}}{120\,\text{V}} = 9.166\ldots \text{ or } 9.17\,\text{amp}$$

Using an allowable voltage drop of 2%, the next step is to determine total allowable resistance:

$$E = IR \qquad R = \frac{E}{I} = \frac{2.4\,\text{V}}{9.1666\ldots\,\text{amp}} = 0.2618\ldots \text{ or } 0.26\,\Omega$$

The total allowable resistance in the extension cord is 0.26 Ω. The next step is to determine the ohms of resistance per 1000 ft:

$$\frac{\Omega}{1000\,\text{ft}} = \frac{0.26\,\Omega}{50.0\,\text{ft}} \times 1000\,\text{ft} = 5.236\ldots \text{ or } 5.2\frac{\Omega}{1000\,\text{ft}}$$

The resistance of a No. 18 wire is 6.51 Ω/1000 feet, and that of a No. 16 wire is 4.09 Ω/1000 feet. Assuming the iron and cord connectors are in good condition, a 25 ft extension cord with No. 16 wire is adequate for the 1100 W iron.

27.5 Selecting Conductor Sizes from a Table

An alternative method for sizing conductors is to use tables provided for that purpose, such as the examples found in Appendixes XIV and XV. These tables have several important limitations. They apply only to wires with insulation types of R, T, TW, RH, RHW, and THW, and they can only be used with a 2% voltage drop and 120 or 240 V. For any other type of conductor, insulation, voltage drop, or voltage, a different table must be used.

Problem Determine the size of wire needed to supply 120 V electricity to the pump house in Fig. 27.1.

Solution The total length of wire is two times the sum of the distance from the building to the first pole (A), the distance between the two poles, and the distance from the last pole to the pump (B). First determine lengths A and B by using Pythagorean's theorem:

$$a^2 = b^2 + c^2$$

Distance A is:

$$\begin{aligned} \text{Distance}_\text{A} &= \sqrt{25.0^2 + 20.0^2} \\ &= \sqrt{625 + 400} \\ &= 32.015\ldots \end{aligned}$$

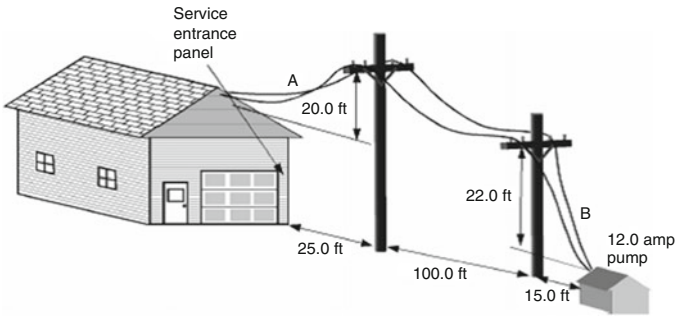

Fig. 27.1 Illustration for sample problem

and distance B is:

$$a = \sqrt{b^2 + c^2} = \sqrt{15.0^2 + 22.0^2} = \sqrt{225 + 484} = 26.627\ldots$$

The total length (L_T) of wire is:

$$L_T = (32.01\ldots \text{ft} + 26.62\ldots \text{ft} + 100.0 \text{ ft}) \times 2 = 317.28\ldots \text{or } 317 \text{ ft}$$

Then using Appendix XIV select the correct size of conductor. Twelve amps and 316 ft are not shown in the table; use the next larger values (15 amps and 350 ft). Then, from Appendix XIV the required size of conductor is No. 3. Remember to compare this value with the value to the left of the vertical line and use the larger of the two sizes.

27.6 Circuit Protection

An important part of any circuit is the over current protection—fuse or circuit breaker. Over current devices are used to prevent the conductors from overheating. Remember, when electricity passes through a resistance, heat is produced, and a voltage drop occurs. As the electrical load on a circuit increases, the heat produced increases, and the voltage drop increases. An electrician determines the total amperage capacity of the circuit and then installs the appropriate over current protection. In the case of an overload or a short in the circuit, the over current device stops the flow of electricity by opening the circuit. If the over current device burns out or trips, the circuit has been overloaded. The load on the circuit must be reduced or the short repaired before the circuit is reenergized.

An additional protection device required by most codes for residential use is the ground fault circuit interrupter (GFCI). A GFCI constantly monitors the difference in the current between the hot conductor and neutral conductor. When the difference reaches 5 mA, the GFCI trips and opens the circuit. This provides more protection to the user of metal cased tools and when using electrical appliances around water. Some agricultural engineers also recommend GFCIs be installed in circuits used around animals. This is especially true for very valuable animals.

27.7 Metric Problems

The common terms used for electricity are the same for both systems, and many European countries also use the AWG standards for sizing conductors. For those individuals that use metric sizes for wires, the resistances for three common sizes are listed in Appendix XIII.

Problem Will a 10.0 amp load on a 120 V circuit with 2.5 mm^2 conductors and a run of 24 m exceed the 2% voltage drop standard?

Solution The first step is to determine the actual voltage drop:

$$E = IR = 10\,\text{amp} \times \frac{0.676\,\Omega}{100\,\text{m}} \times (24\,\text{m} \times 2) = 3.244\ldots\ \text{V}$$

The second step is determining the percentage:

$$\frac{3.244\ldots\ \text{V}}{120\,\text{V}} \times 100 = 2.704\ \text{or}\,2.7\%$$

The load is not acceptable for a circuit limited to 2% voltage drop but is acceptable if the voltage drop for the circuit is 3%.

Chapter 28
Electric Motors

28.1 Objectives

1. Be able to explain the advantages and disadvantages of electric motors as a power source.
2. Understand the use and performance classifications of electric motors.
3. Be able to describe the common types of motors.
4. Be able to select the correct overload protection device for the application.
5. Be able to interpret a motor nameplate.

28.2 Introduction

An electric motor is a machine that converts electrical energy to mechanical power. Modern agriculture is heavily dependent on the use of electric motors. Managers of agricultural production systems should know the common types of motors and be able to select the correct motor. Manufacturers have gone to great lengths to design motors to meet the needs of agriculture. The life of an electric motor is determined by how well the motor is matched to the job and the service environment. The following sections will discuss the characteristics and uses of 120/240 V, single-phase motors.

28.3 Electric Motors

An electric motor is an energy conversion device like internal combustion engines, but instead of using the energy in a liquid fuel, they use energy supplied by electricity. An electric motor requires an interaction between the rotating parts and the stationary parts. Two types of interaction are conduction and induction. The principles of a conduction motor will be used to explain the function of electricity motors.

Electricity flowing through a conductor induces an electrical magnetic field around the conductor. This electromagnetic field will have a plus (+) and a

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H.L. Field, J.M. Long, *Introduction to Agricultural Engineering Technology*,
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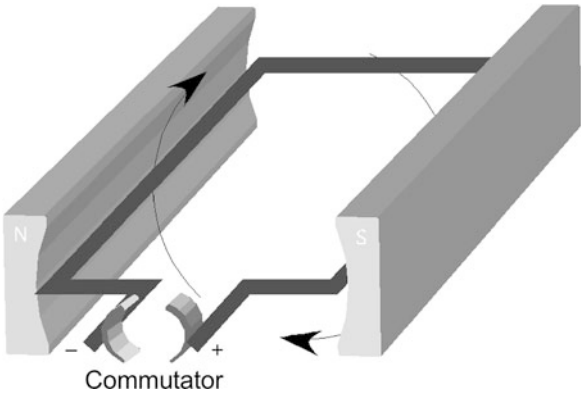

Fig. 28.1 Simplified electric motor

minus (−) polarity. When an electromagnetic field comes in contact with a permanent magnetic field, supplied by the magnets, a force is produced when similar polarities are in close proximity because they repel each other. When opposite poles are also in close proximity, a force is produced because they attract each other. The strength of the force is influenced by the strength of the current, the strength of the magnetic field, and the angle between the conductor and the magnetic field (Fig. 28.1).

In Fig. 28.1, the commutator supplies electricity to the loop of wire. The electromagnetic field reacts with the permanent magnetic field supplied by the permanent magnets. This causes the wire loop to rotate. A conductive electric motor has many individual loops wrapped around the rotor, and each one of them rotates a few degrees when they are sequentially energized by the commutator. Because a continuous series of loops become energized, the rotor continues to rotate as long as power is being supplied to the commutator.

Many different types of motors are used, and they are categorized by their type of electricity and the type of interaction they have between the rotating part and the stationary part of the motor. The following sections will discuss some of the advantages and disadvantages of electric motors.

28.4 Advantages and Disadvantages

28.4.1 Advantages

Electric motors have several advantages that have made them more popular than other sources of power:

1. *Initial cost*: On a per-horsepower basis the purchase price of an electric motor is relatively low.
2. *Design*: Electric motors have very few parts and are very easy to operate. In addition, because they are started and stopped with switches, their operation is easily automated.

3. *Operating costs*: The operating costs of electric motors are low. They have very low maintenance costs, and the cost of electricity allows them to be operated for a few cents per horsepower hour.
4. *Environmental impact*: An electric motor gives off no exhaust fumes and does not use a flammable fuel, and although it is true that the generation of electricity may affect the environment, it is easier to monitor and control this effect if it is concentrated at one location.
5. *Noise*: Electric motors operate quietly with very little vibration.
6. *Efficiency*: An electric motor is the most efficient way to produce power, operating with an efficiency range of 70–90%.

28.4.2 Disadvantages

1. *Portability*: Electric motors are not very portable; they must be connected to a source of electricity. Advances in battery design have reduced this disadvantage for fractional horsepower DC motors, but AC motors must be connected to a source of alternating current.
2. *Electrical hazard*: Electricity has an adverse effect on humans and other animals when they come into contact with it. With the large number of motors used in agriculture and the tendency for the environment of agricultural structures to be wetter and dustier than residences, there is a greater electrical hazard associated with the use of electrical motors in agricultural buildings.

28.5 Use and Performance Classifications

The following use and performance classifications provide a basis for comparing different types of electric motors.

28.5.1 Type of Current

Motors can be purchased to operate on either single phase or three phase, direct, or alternating current, at several voltages. The voltage and the type of current used depends on the size of the motor and the electrical service available. The phase refers to the number of cycles of alternating current (Fig. 28.2).

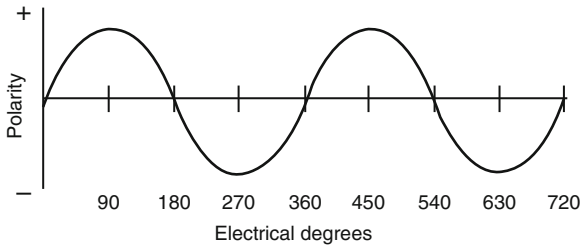

Fig. 28.2 Two complete cycles of single-phase alternating current

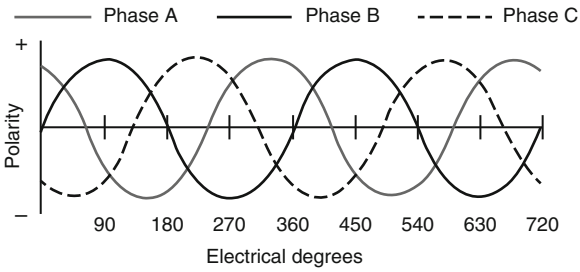

Fig. 28.3 Two complete cycles of three-phase alternating current

Three-phase alternating current has three single-phase currents combined, so the peak voltages are an equal distance apart; see Fig. 28.3.

Three-phase current is recommended over single phase for larger loads and is required by most electrical service companies for motors over 5–10 horsepower.

28.5.2 Type of Enclosure

The primary enemies of motors are liquids, dust, and heat. Motors are designed with different enclosures (cases) to operate in different environments. A drip-proof motor has vents and will operate successfully even if water occasionally drips on it. In a splash-proof motor, the vents are protected from both drips and splashes. Drip-proof and splash-proof motors usually have an internal fan that draws air through the motor to help prevent overheating. A totally enclosed motor can be used in wet, dusty environments because it has no vents; thus, the air has no access to its internal parts. All of the heat generated inside the motor must be conducted to the outside surface and dissipated into the air. Some totally enclosed motors have a fan mounted outside the case to increase the air flow (cooling) around the motor enclosure.

28.5.3 Type of Bearings

Motors are constructed with either sleeve or ball bearings. Sleeve-bearing motors are less expensive than ball-bearing motors but can withstand less force perpendicular to the shaft (belt tension, etc.) than ball-bearing motors, and the life of the bearings is usually shorter unless they can be lubricated.

28.5.4 Type of Mounting Base

Electric motor manufacturers have standardized the mounting brackets for motors. When replacing a motor, if the same base style is used, no modifications should be required for the motor mounts.

28.5.5 Load-Starting Ability

Some electrically driven machines offer little resistance to rotation when they are started. These loads are said to be easy to start. Other machines offer greater torsion resistance when starting and are considered to be loads that are hard to start. The amount of torque required to start a machine depends on the type, size, and operating characteristics of the particular machine. Thus, some knowledge of the starting characteristics of a load is necessary to select the correct motor.

28.5.6 Starting Current

Motors require more current to start a load than they do to operate the load once it is rotating. The starting current required may be seven to eight times the operating current. The starting current of motors is classified as low, medium, or high.

28.5.7 Reversibility

Electric motors can be designed to operate in either a clockwise or a counterclockwise direction of rotation, but some motors can have the direction of rotation changed by electricians. These are classified as electrically reversible or mechanically reversible.

28.5.8 Dual Voltage Potential

If a motor is dual voltage, it can be operated on either 120 or 240 V. The voltage used is determined by the voltage available from the source. Motors operating on 240 V are more efficient and require smaller conductors than those operating on 120 V.

28.6 Types of Motors

A description of each of these types of motors and information on selection of the ideal type for a specific situation is beyond the scope of this text. Each of these types of motors will have specific advantages and disadvantages for specific applications (Fig. 28.4).

Three of these types of motors are more common in agricultural applications than the others. These types are listed in the following sections with a short description of each type.

28.6.1 Split Phase

Split-phase motors are inexpensive and are used for easy-to-start loads. The starting current may be as high as seven times the operating current, depending on the load. They are very popular for powering fans, centrifugal pumps, and other applications

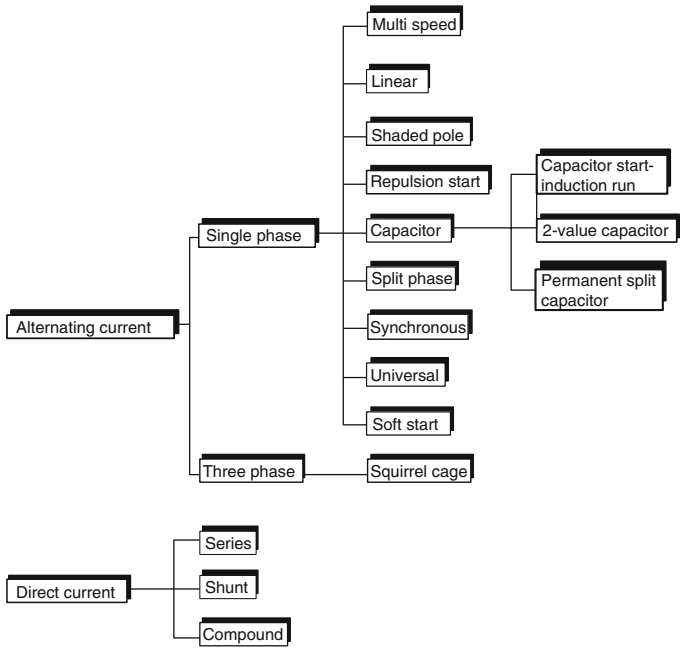

Fig. 28.4 Common types of electric motors

where the load increases as the speed increases. The common sizes are 1/6–3/4 horsepower.

28.6.2 Capacitor Motor

A capacitor motor is a split-phase motor with the addition of capacitors to increase the starting and/or running torque. Capacitor motors are the most widely used type in agricultural applications, particularly in the smaller sizes of less than 10 horsepower.

28.6.3 Repulsion Motors

Repulsion motors are used for hard-to-start loads. Two variations of the basic design are used: repulsion-start induction-run and repulsion–induction. The use of brushes and the additional design requirements cause repulsion motors to be the most expensive type. They are available in a wide range of sizes.

28.7 Overcurrent Protection

Overcurrent devices (fuses or circuit breakers) in the service entrance panel of a building are designed to protect the circuits from shorts and excessive current. Standard overcurrent devices will not work for circuits powering some electric motors because the starting current of electric motors is greater than the operating current, which causes a temporary overload on the circuit. In addition, when an electric motor is overloaded, it will attempt to rotate until the electricity is disconnected or the lock-up torque is reached. Both of these situations can cause an excessive current in a circuit powering a motor. The overcurrent devices must be designed to withstand temporary overloads. Common breakers and fuses do not meet these requirements. Motor circuits must be protected by time delay fuses or breakers.

28.8 Overload Protection

When a motor is overloaded for an extended period of time or on a frequent basis, it will overheat. Some motors include an overload protection device to protect the motor from overheating. These devices work on the principle of resistive heating. Because the current demand of a motor increases as the load increases and because the greater the current flow through a resistance the greater the heat, engineers can predict when certain temperatures will be reached and design controlling devices using temperature as the trigger.

Three types of motor overload protection devices are used:

1. *Built-in thermal overload protection*: Many motors have this device as an integral part of the motor. It may have either an automatic reset or a manual reset. If the automatic reset type is used, the device will disconnect the motor from the circuit at the designed temperature, and when it has cooled down, it will automatically reconnect the electricity. This type of device should be used where the motor is supplying power for a critical purpose such as livestock ventilation fans and sump pumps. Automatic reset devices can be more dangerous than manual because they will attempt to restart the motor as soon as they cool down. If the power is not disconnected before anyone works on the machine, it can restart during repairs and cause injury. When the motor has a noncritical function, it should have a manual reset thermal overload. Manual reset eliminates the possibility of the motor restarting when someone is working on it. An exception is a motor mounted in a location that makes it difficult to manually reset the motor.
2. *Manual starting switch with overload protection*: A manual starting switch overload protection device can be added to motors without built-in thermal protection. This device is an integrated switch and thermal overload device that opens the circuit when the motor overheats. It must be reset by hand before the motor can be restarted.

3. *Magnetic starting switch with overload protection*: Magnetic starting switches are used to switch the current for large horsepower motors. They are fast-acting switches and can be equipped with a thermal overload (heater) device that will open the circuit if the current draw is excessive. These devices are manually reset.

28.9 Motor Nameplate Data

The National Electrical Manufacturers Association (NEMA) has developed a standardized system of identifying the important characteristics of motors. The standards do not specify a shape or location for the nameplate or the information that it must contain, but the information that is important for motor selection will be included, see Fig. 28.5.

The following list of terms covers some of the information that can be found on motor nameplates:

Manufacturer:	The company name and address are included to provide a source of further information.
Horsepower:	The designed full-load horsepower rating of the motor is given.
Serial number:	The serial number is included to facilitate the procurement of parts when they are needed.
Frame:	Standard frame numbers are used to ensure that the motors are interchangeable. If the frame number is the same for two motors, the mounting bolt hole pattern will have the same dimensions.
Speed:	The speed is in revolutions per minute (rpm). It is the designed speed at which the motor will operate under a full load.
Phase:	This indicates whether the motor is designed for single- or three-phase power.

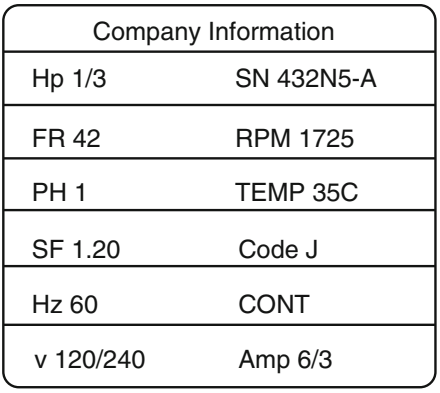

Fig. 28.5 Typical motor information

Temperature:	This is the maximum ambient temperature for the motor operating at design load.
Service factor:	The service factor indicates the safe overload limit of the motor. An SF of 1.20 means that the motor can be operated continuously with a 20% overload without damage.
Code letter:	The code letter is used to indicate the size of the overload protection device that will be needed.
Hertz:	This indicates the designed operation frequency of the electrical supply. It is shown as 60 cycles or 60 hertz.
Duty rating:	Motors will be rated for either continuous or intermittent duty. If the rating is for intermittent duty, the nameplate may also indicate the maximum amount of time that the motor can be continuously operated without a cooling period. Exceeding the duty cycle will cause the motor to overheat.
Voltage:	The operating voltage for the motor will be indicated. If the nameplate contains only a single value, the motor is not dual voltage.
Amperage:	This indicates the current demand at full load. If two numbers are given, it indicates the amperages for the two voltages listed. For example, in Fig. 28.5, the amperage is listed as 6/3. This means that when the motor is wired for 120 V, the full load amperage is 6 amps, and it is 3 amps when the motor is wired for 240 V.

Chapter 29
Site-Specific Crop Management

29.1 Objectives

1. Explain how site-specific crop management is used in production agriculture.
2. Understand how satellites are used to calculate position.
3. Explain how spatial data is used in crop management.
4. Be able to describe the difference between directed and grid soil sampling.
5. Understand how crop yield monitors are used to collect yield data.

29.2 Introduction

Site-specific crop management can be defined as a crop production system focused on the collection and use of temporal and spatial data to manage and tailor crop needs specific to that crop's location or site using variable application techniques. This type of crop management system requires that data be collected alongside specific location information (spatial data) while continuing to collect this data to compare each crop year or multiple times throughout the season (temporal data). Many of the technologies used in this type of crop management system are sometimes called precision agriculture tools since they are able to measure and analyze at much finer resolution than traditional production methods. This chapter covers a few of the basic topics directly related to site-specific crop management.

29.3 Global Navigation Satellite Systems

In recent years, the use of global navigation satellite systems (GNSS) has become commonplace. A GNSS receiver chipset is incorporated into many modern day electronics to provide location information for a variety of purposes. The first GNSS system available for use in the United States was the global positioning

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H.L. Field, J.M. Long, *Introduction to Agricultural Engineering Technology*,
https://doi.org/10.1007/978-3-319-69679-9_29

system (GPS). Public availability of GPS has transformed the way in which we produce the food, fiber, and feed in the agricultural industry.

The GPS consists of three distinct segments: space, control, and user. The space segment includes a minimum of 24 active satellites that complete two earth orbits per day. This type of orbit means that each satellite passes over the same part of the earth once each day and provides a minimum of six viewable satellites anywhere on the earth's surface. Each satellite contains an atomic clock and broadcasts its current position along its orbit and the current time of broadcast. The control segment is composed of the master control station, ground-monitoring stations, and ground-broadcast antennas. The satellites are monitored for correct orbit and clock accuracy. Any adjustments are sent to the satellites through the ground-broadcast antennas. Most people only interact with the user segment since GPS is a single direction (receive only) signal that is processed by the individual receiver chipsets. The only other global GNSS currently in operation is Russia's GLONASS. The Chinese BeiDou and European Union Galileo GNSS are scheduled to be fully functional by the year 2020.

All GNSS receivers determine their location by calculating their distance from each satellite in view. Using the speed of light as the signal velocity and the difference in time between the time when the signal was received and when the satellite began its broadcast, a receiver can calculate its distance from the satellite. With a minimum of three distances, the receiver can calculate its position in three dimensions. A fourth satellite is needed to calculate the difference in time between the satellite atomic clock and the receiver clock. Additional satellites beyond four will improve location accuracy by providing duplication to eliminate inherent errors. Newer receivers are also able to use multiple GNSS such as GPS and GLONASS to expand the number of satellites available at any one time.

29.3.1 Accuracy

The positional accuracy of a GNSS receiver is very important when we choose to use the location data for other tasks. GNSS receiver accuracy can be measured in three different ways: absolute accuracy, pass-to-pass accuracy, and static accuracy. Which of these three measurements is most important depends on the task?

Absolute accuracy is a direct measurement of the GNSS receiver's ability to correctly identify where it is located on the planet. A GNSS receiver with a high absolute accuracy would be able to calculate position coordinates (latitude/longitude) within a small error of the actual position coordinates of the receiver. For example, a surveying receiver might have an advertised absolute accuracy of 2 inches. This would mean that any coordinates calculated by the receiver should be within a 4-inch diameter circle or ± 2 inches of the actual position coordinates. This type of accuracy is important for surveying areas or locating objects, but for most agricultural task, only relative accuracy is necessary.

Pass-to-pass or relative accuracy is what most users of GNSS receivers in the agricultural setting consider when selecting a unit. Pass-to-pass accuracy is a measure of the receiver's ability to return to or with in a set distance of a point that was calculated no more than 15 min previously. The name is derived from the idea that a typical swath or pass in a field would be within 15 min of the last. This type of accuracy value will typically be what manufactures of agricultural GPS receivers list as their given accuracy because swath guidance is highly influenced by pass-to-pass accuracy.

Problem What would be the minimum and maximum distance between the center line of two parallel swaths for a tractor guidance system with a GNSS receiver that has an advertised pass-to-pass accuracy of 5 inches? Assume a target swath of 20 feet.

Solution In a perfect world, the two parallel swaths would be spaced exactly 20 feet on the center for their entire length. Since the GNSS system has a pass-to-pass accuracy of 5 inches, the coordinates could have an error of ±5 inches. Assuming the new pass is within 15 min of the old pass, the minimum distance is calculated by subtracting the error from the swath:

$$\text{Min} = 20'0'' - 5'' = 19'7''$$

The maximum distance is calculated by adding the error to the swath:

$$\text{Max} = 20'0'' + 5'' = 20'5''$$

On each path the equipment could vary between overlapping by 5 inches and leaving a 5 inch skip and be considered acceptable performance.

In many situations, measurements must be made, or points must be found well after 15 min have elapsed since the position coordinates were last calculated. In these cases the static accuracy or repeatability of the system must be considered. Since the GNSS is a dynamic system, longer elapsed times between measurements introduce the chance of changes in atmospheric conditions, satellite errors, satellite configuration changes, or other local interferences. The static accuracy of a GNSS receiver will determine how close the unit can locate a previously calculated location later in the season or even the following season. Typically static accuracy will be the same or worse than the pass-to-pass accuracy for a given receiver.

29.3.2 Type of Receiver

Standard GNSS receivers are typically not very accurate due to the number of errors possible when calculating a position. To improve their accuracy, receivers typically utilize some type of correction signal. Correction signals are calculated using stationary towers located locally or some distance from the receiver that are on known points. These correction signals can be broadcast from these towers or

relayed to stationary satellites that then rebroadcast the correction solution. There are several publically available correction signals. In the United States, the Wide Area Augmentation System (WAAS) is the most common satellite-based augmentation system (SBAS). Many companies also offer SBAS correction signals through subscription services that may offer greater accuracy or repeatability than WAAS.

High accuracy (less than 1-inch error) requires a correction tower within a couple miles of the receiver. Real-time kinematic (RTK) systems use two GPS receivers located near each other. One receiver, the base, acts as the correction tower by calculating and broadcasting corrections to the second receiver, the rover, which is mounted on the tractor or equipment that requires high positional accuracy. RTK systems have historically been cost prohibitive in many applications, but advances in technology have made these systems more affordable for agricultural guidance systems such as auto steer.

29.4 Automation

One of the first and most widely accepted use of a GNSS receiver on agricultural equipment is to provide guidance. Swath guidance is the most prevalent type found on agricultural equipment. This type of guidance system provides visual or auditory indication of how close the current travel path is from the planned travel path. Typically the driver would then need to make the necessary adjustments to realign with the planned travel path. This guidance system is carried one step further in machinery equipped with some type of auto-steer system. Auto-steer systems follow the planned swath by using a computer to read, calculate, and adjust the travel path to minimize the amount of error between the planned path and the actual path. Most auto-steer systems can handle straight-line and contour swaths but require operator intervention to move to adjacent paths at headland turns.

Being able to calculate the position of a piece of equipment in real time has other applications on the implement side. In sprayer systems, sprayer booms can be plumbed to allow independent control of a section of nozzles or individual nozzles. By knowing the calculated position of the boom during application, individual nozzles or boom sections can be disabled to prevent overspray when they enter areas of the field where application has already occurred. Similar section and individual row unit control is available on precision planters to prevent planting areas that have already been planted such as a headland turns or irregular shaped fields or even vary the seeding rate while planting to adjust plant population to field conditions. With individual nozzle control, the ability to make rate changes on the go is possible. This ability allows systems to change or vary the application rate based upon equipment position in the field. Variable rate application is one of the goals of site-specific crop management and will be discussed later in this chapter.

29.5 Spatial Data

One of the major uses of global position is in the generation of spatial data. Spatial data is any piece of data that can be tied back to a position in the field or a set of coordinates. Spatial data allows information such as nutrient availability, pH, yield, moisture, and other measureable variables to be attributed to a specific location in a field. Spatial data allows fields to be managed at a much smaller, more precise scale than crop management systems have historically allowed. This section will be limited to only a few items out of a multitude of data types available to agricultural producers.

29.5.1 Soil Sampling

Soil sampling is one of the most common management tools available. Conventional methods of soil sampling require management zones be identified where composite soil samples are collected in multiple locations across the zone. In conventional soil sampling methods, these zones would be identified using past productivity, topsoil color, or past management such as an area of a field historically used for manure disposal. These conventional zones tend to be larger and somewhat subjective in their location or boundaries. With the availability of spatial data from almost every piece of equipment that crosses a field, management zones can be much more precisely defined.

One example is the use of soil sensors that can measure and report some soil properties without sending samples to the lab. One of the most common soil sensors is equipment-mounted soil electrical conductivity (EC) sensors. These sensors can be either contact or noncontact types. Contact types usually use at minimum a pair of electrodes with one electrode applying electrical current into the soil profile and a second measuring the voltage drop at a set distance away. Noncontact EC sensors use at minimum a pair of coils placed a set distance above the soil's surface. One coil generates a magnetic field, which in turn causes current to flow in the soil profile. As current flows in the soil profile, it generates a secondary magnetic field that the second coil is able to detect and measure. The magnitude of the secondary magnetic field is related to the ability of the soil to conduct and allows the calculation of a soil EC value.

Directed soil sampling is a method of using spatial data such as yield, soil EC, aerial imagery, etc. to definite more specific management zone with areas of commonality among the data. Figure 29.1 is an example of a field that has used a soil sensor to collect soil EC transects. Typically transects will be spaced 40 ± 20 feet apart. This swath width will identify enough of the variability in a particular field at a scale that can be managed well.

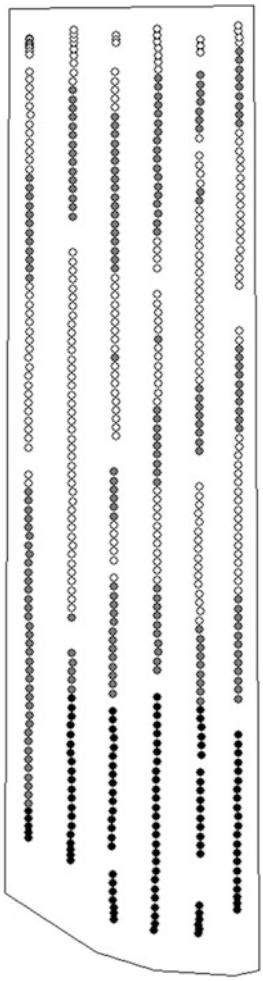

Fig. 29.1 Data output for soil electrical conductivity

The data points in these transects are then interpolated to generate a map of the entire field (Fig. 29.2). Within these management zones, a predetermined number of composite soil samples are chosen and collected. In Fig. 29.2, six soil samples per zone type are selected to identify the soil properties of each zone. Soil samples from each of these six areas can then be collected to form a composite sample. The laboratory soil test values for this composite will then be used as the average values for the entire management zone.

Sometimes good spatial data is not readily available such as a field brought back into production or a newly acquired field. Other times more precision is desired such as fields that have had significant grading work or heavy organic incorporations like animal manure. In these cases, grid sampling would be the preferred method of collecting accurate and precise soil data. Before the use of soil sensors

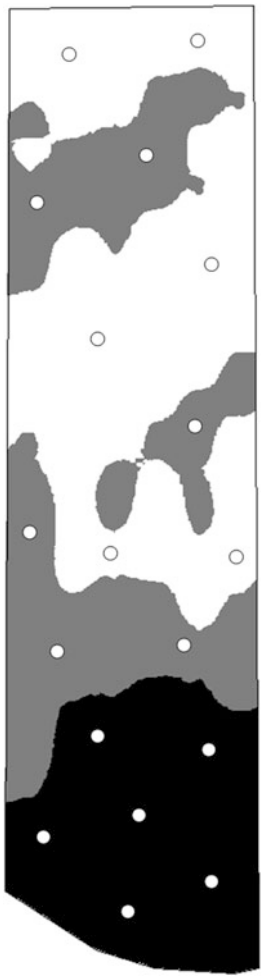

Fig. 29.2 Soil sampling locations for a directed soil sampling method

and other spatial data, grid sampling was the most commonly used method of generating precise soil maps for fields. Grid sampling requires dividing the field into a predetermined grid. At the intersection of each grid line, a soil sample is collected. Figure 29.3 is one way in which grid sampling points might be assigned on the field used in the previous discussion.

The vertical and horizontal spacing of the sample points will be determined by the precision, collection time, and cost. For larger production fields, the grid may be spaced to collect one sample per three to four acres. In smaller field or areas where more precision is needed due to known variance across the field, the grid may be spaced to collect multiple samples per acre.

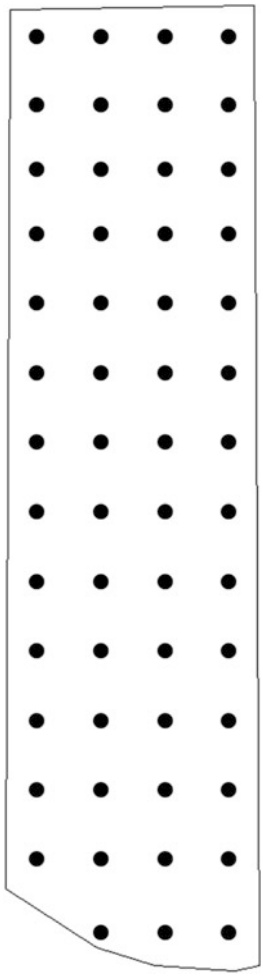

Fig. 29.3 Soil sampling locations for a grid sampling method

29.5.2 Yield Monitors

Crop yield is an important data point that can help improve the decision-making process. Figure 29.4 is an example of how a yield map might show variations in yield across a field based upon factors such as soil type, properties, moisture, etc.

Yield maps such as these can be collected each year to provide historical yield data and make more informed decisions on management zone boundaries. All of this yield data is collected on the harvester using some type of yield monitoring system. This section will cover a few of the different sensors that compose such as system.

Fig. 29.4 Yield map generated from yield monitor data

29.5.2.1 Mass Flow Sensor

Mass flow sensors measure crop yield by measuring the mass of the crop over time as it passes through the harvester. Mass flow sensors are very common on grain combines and are typically located near the top of the clean grain elevator. The most common type found on combines in the United States is the impact plate flow sensor (Fig. 29.5).

As the name suggests, impact plate sensors are located so that as grain is thrown from a clean grain elevator paddle, it strikes the impact plate. The impact force is measured by the sensor and converted to a mass. The impact plate sensor must be calibrated by measuring and weighing multiple loads of grain collected at different flow rates through the combine.

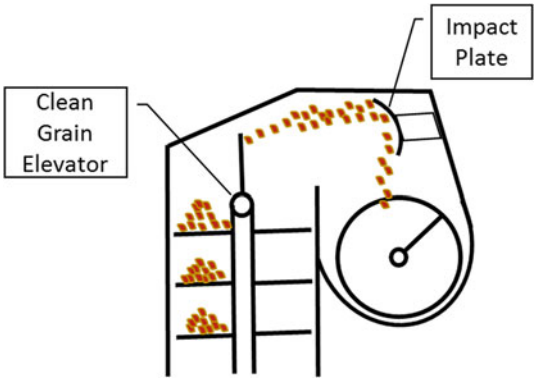

Fig. 29.5 Impact flow sensor in a grain combine

Figure 29.6 presents a similar flow sensor used by some combines in the European market. This radiometric flow sensor uses a small radiation source and detector. The amount of radiation that passes through the grain to the detector is correlated with the mass of grain passing between them. The exposure of the grain to radiation and the perceived side effects have limited this type of sensor in combines used in the United States.

A simple equation to express the harvest yield in bu/ac for a crop measured by a mass flow sensor is

$$Y = \frac{m \times 29{,}700}{t_w \times w \times v}$$

where Y = harvest yield (bu/ac); m = mass flow rate of harvest (lb/s); t_w = standard test weight of the crop (lb/bu); w = harvest width (ft); v = forward harvest velocity (mi/h); 29,700 = unit conversion value.

Typical test weights for selected crops can be found in Appendix XVI.

Problem What would be the calculated yield at the point in time when the in-cab monitor on a combine with a 30-foot header displays a flow of 17.5 lb/s while harvesting wheat traveling 4.0 mi/h?

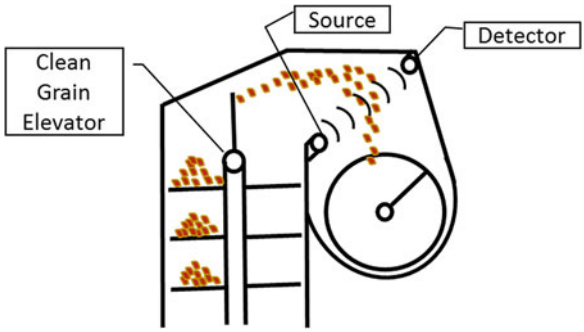

Fig. 29.6 Radiometric flow sensor in a grain combine

Solution Using Appendix XVI the test weight, t_w, for wheat is 60 lb/bu. Substituting this into the harvest yield equation along with the width, forward harvest velocity, and mass flow rate of harvest:

$$Y = \frac{17.5 \times 29{,}700}{60 \times 30 \times 4.0}$$

$$Y = 72.1875 \text{ or } 72 \text{ bu/ac}$$

At this particular point in the field, the yield monitor would be harvesting wheat that is producing on average 72 bushels per acre.

29.5.2.2 Volumetric Flow Sensor

Some crops, like cotton for example, do not lend themselves well to measurement of a force on an impact plate. Yield can be calculated much more accurately by measuring the volumetric flow of the crop material in the harvester. The volume of crop passing a selected point in the harvester is typically measured using an optical or photoelectric sensor. These sensors typically project a beam of light across an opening and detect how much of the light is being blocked by crop material (Fig. 29.7). This is similar to how the sensors you may see on a garage door that prevent the door from closing on someone.

In addition to crops harvested such as cotton or silage that lend themselves to an optical yield sensor setup such as the one presented in Fig. 29.7, some older grain combines are retrofitted with optical sensors and moisture sensors directly in the clean grain elevator (Fig. 29.8).

The optical sensors are able to measure the amount of grain lifted by each paddle as they move up the clean grain elevator. The only drawback with this type of sensor is that the grain level might be incorrectly measured if the combine is

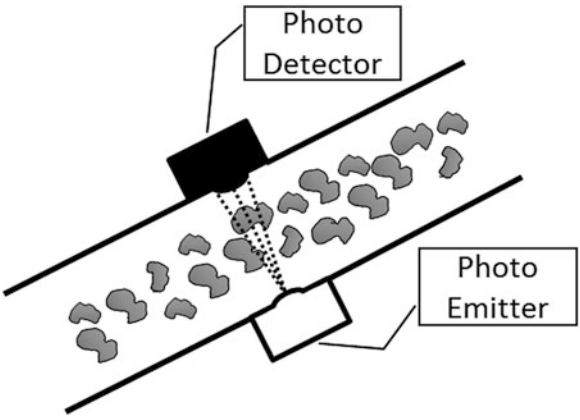

Fig. 29.7 Optical flow sensor in a cotton picker

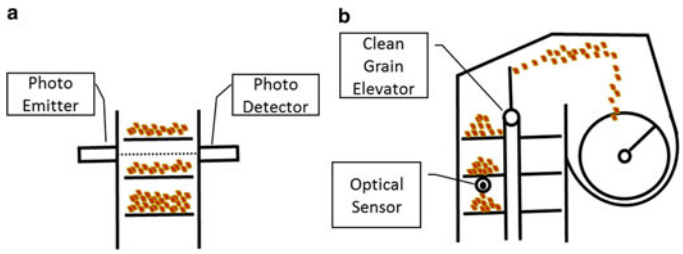

Fig. 29.8 Front (**a**) and side view (**b**) of an optical sensor for a grain combine

harvesting in a field where the clean grain elevator is no longer close to vertical, such as a hillside.

A simple equation to express the harvest yield in bu/ac for a crop measured by a volumetric flow sensor on a grain combine is:

$$Y = \frac{q \times 13.8}{w \times v}$$

where Y = harvest yield (bu/ac); q = volumetric flow rate of harvest (in^3/s); w = harvest width (ft); v = forward harvest velocity (mi/h); 18.8 = unit conversion value.

Problem What would be the calculated yield for a six-row corn head traveling 2.5 mi/h if the optical sensor is measuring a flow of 570 in^3/s in the clean grain elevator? The field was planted on 30-inch row spacing.

Solution First, the harvest width must be determined using the row spacing and the number of harvested rows:

$$w = \frac{6 \text{ rows}}{\text{swath}} \times \frac{30 \text{ in}}{\text{row}} \times \frac{1 \text{ ft}}{12 \text{ in}} = 15 \text{ ft}$$

Substituting this into the harvest yield equation for volumetric flow sensors along with the forward harvest velocity and volumetric flow rate of harvest:

$$Y = \frac{570 \times 13.8}{15 \times 2.5}$$
$$Y = 209.76\ldots \text{ or } 210 \text{ bu/ac}$$

29.5.2.3 Moisture Sensor

In most cases, the harvest moisture content is not equal to the moisture content used to determine the standard test weight. For example, corn harvested at maturity could have a moisture content greater than 25 %MWB where the standard test

weight is determined at a moisture content of 15.5 %MWB. The additional water will increase the density and skew the actual yield in bushels when much of this water is removed prior to marketing.

Moisture measurement sensors are a common part of most yield monitors. Moisture sensors may measure moisture continuously in the clean grain elevator or draw only a small sample on a regular interval. Using the moisture measured directly during harvest, yield can be adjusted for the moisture difference between the harvested moisture and the standard moisture at market. The following equation is used to calculate the adjusted yield:

$$Y_{\text{adj}} = Y \times \frac{100 - M_{\text{harvest}}}{100 - M_{\text{market}}}$$

where Y_{adj} = adjusted yield value for moisture difference (bu/ac); Y = harvest yield (bu/ac); M_{harvest} = wet-basis moisture content measured at harvest (%MWB); M_{market} = wet-basis moisture content of material at point of sale (%MWB).

Problem Soybeans were harvested at a moisture content of 17 %MWB. The yield monitor displays a 55 bu/ac yield at harvest. What would this yield at the elevator, at standard moisture?

Solution Using Appendix XVI the standard moisture content is 13 %MWB for soybeans. Substituting this into the adjusted yield equation for moisture differences:

$$Y_{\text{adj}} = 55 \times \frac{100 - 17}{100 - 13}$$

$$Y_{\text{adj}} = 52.47126\ldots \quad \text{or} \quad 52\ \text{bu/ac}$$

After drying the soybeans down to a standard 13 %MWB, there is a three bu./ac reduction in the yield.

29.5.2.4 Forward Speed Sensor

Accurate harvest speed is crucial to predicting yield at any point during harvest. Forward harvest speed, in combination with the harvest width, determines how fast an area is covered. Yield monitors then use the forward harvest speed to calculate the yield at that particular point in time using the harvest yield equation discussed earlier. There are three common types of sensors implemented on harvesters by the original manufacturer or as an aftermarket addition. These sensors are radar, hall effect, and GNSS.

Radar units are usually self-contained and can be found on several aftermarket yield monitor systems. Radar units use a similar principle to ones used by law enforcement, except the radar unit is moving with the harvester instead of stationary. Most units transmit a pulsed electrical signal that varies the frequency of the pulses with the speed of the ground passing below the unit. The monitor can then

interpret the signal and calculate a speed using a predetermined calibration algorithm.

Hall-effect sensors are used to measure the rotational speed of a shaft. Typically, they are installed facing an exposed gear or sprocket. Sometimes a sheet metal disk with a set number of evenly spaced teeth is installed on the shaft when no other options are available. The sensor transmits a pulse each time a gear tooth passes near the sensor. Using the number of teeth on the gear and the timing of the pulses, a shaft rotational speed can be calculated. The rotational speed of the shaft such as an axle or other drivetrain components can be converted to forward speed by taking into consideration any further gear ratio changes and the tire size of the harvester. Any slip between the tire and the soil surface can introduce error with this type of sensor.

Since some type of GNSS system is already being used to determine and record location, forward speed can be calculated. Most receiver units can calculate speed using the current position, previous position, and the time elapsed between those two points. One of the drawbacks of this type of speed calculation is that there is an inherent lag associated with the calculation since it requires, at minimum, two position points before a calculation can be made.

29.6 Variable Rate

One of the main goals of a site-specific crop management system is to be able to leverage all of the data collected on a particular location to provide the proper growing environment for a crop without using more of a particular input than is necessary. Properly balancing inputs increases profit margin and reduces environmental impact by reducing wasted resources applied to crops that will not increase their yield potential. The most common way of balancing these inputs is through some type of variable rate application. This might mean using a variable rate fertilizer spreader that can vary the amount applied as the spreader traverses a field based on crop needs. Variable rate liquid sprayers can adjust the amount of liquid applied as needed. This might also allow for varying amounts of in-season side dress fertilizers to be applied or allow preemergent herbicides to be varied based on soil organic matter changes across a field. Some newer irrigation systems allow the amount of water applied to be adjusted based on soil moisture or crop evapotranspiration rates. All of these are great examples of how variable rate application systems can be utilized, but the common factor is that some sort of decision must be made to set the rate across the field and decision-making requires data and algorithms to process the data. There are two major types of variable rate systems: real-time and post-processed. These two systems use the current or historical data collected in different ways.

29.6.1 Real-Time

Real-time variable rate systems use some type of equipment mounted or wirelessly connected sensors. These sensors provide data at the same time as the equipment applies product on the field. In most systems, the collected data is immediately processed through an algorithm on an onboard computer, and a decision rate is selected for immediate instruction to the rate controller.

One example of real-time variable rate application is the use of an active light sensor on the front of the applicator to measure and calculate a normalized difference vegetation index (NDVI) to predict nutrient requirements of the crop. This NDVI value can then be processed through an algorithm, and a prescribed fertilizer rate can be applied to the crop immediately. The spacing between the sensor and the application point on the equipment requires the processing time and forward speed be taken into consideration. One of the advantages to this type of system is that a GNSS system is not necessarily required, but having an "as applied" map for future management decisions is always helpful, so GNSS systems are typically still included.

A similar type of setup can be utilized by stationary irrigation systems such as a center pivot sprinkler. A network of infield sensors can determine crop needs and relay that information to the pivot towers to adjust the application rate as the pivot nears the sensor location.

29.6.2 Post-Processed

Unlike real-time variable rate systems, post-processed variable rate application systems require that all data collection and processing occur before any application begins. Spatial data such as yield, soil sampling, and other sensor data is post-processed or processed after collection. The result of the post-processing is the generation of a prescription map. A prescription map holds the information necessary for the variable rate controller to make rate changes as the applicator traverses the field. Prescription maps can be generated for fertilizer application, but the process is beyond the scope of this text. Variable rate lime application is a much more straightforward process and will be discussed in this section.

Soil pH is typically adjusted through the application of some type of limestone product. Limestone is used to increase the soil pH value since most soils tend to become more acidic over time. Improper pH levels, both too high and too low, can make some soil macronutrients and micronutrients inaccessible to plants. Improper pH can also increase the availability of certain elements, such as aluminum or manganese, to a level that is actually toxic to the plants. The need to apply lime and the amount necessary are typically indicated in a standard soil laboratory test. Referring back to the previous section on soil sampling, conventional soil sampling suggests that soil cores should be selected across the field and then mixed together to form a composite sample for the entire field. This sample is then processed by a

soil laboratory. The test report will list the current soil pH and give a recommendation for a liming rate if necessary.

For variable rate liming, soil samples must be collected using either the grid or directed sampling procedure discussed earlier. The recommended rates can then be plotted on the map, and a rate prescription map can be generated for the variable rate applicator (Fig. 29.9).

In this particular example, three different application rates were selected based upon the soil sample results: 1, 2, and 4 tons per acre. If the conventionally sampled recommendation was around 2.25 tons per acre, over half of the field would result in over application and the remainder, under application. The total amount of lime

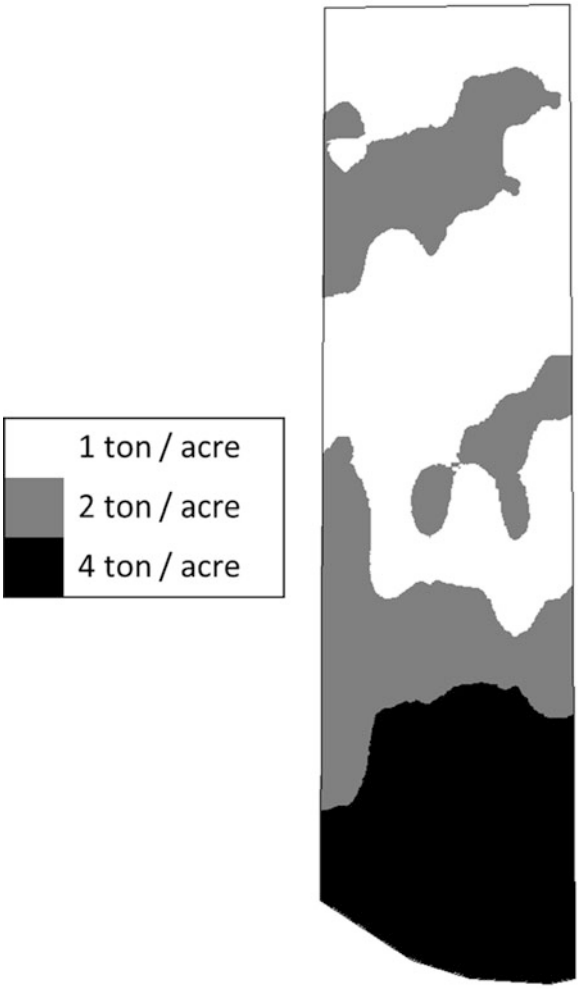

Fig. 29.9 Prescription map for lime application using soil sampling data

used for the field might be close to the same, but with the variable rate application, the material can be placed more precisely where it is needed. One of the advantages of using prescription maps over real-time sensors is that the equipment is much simpler and prescription maps can be generated by agronomic consulting firms with little need for the producer to get involved in the specifics of processing data. For post-processed variable rate application systems to be time and cost effective, the data used for processing must be accurate and of high quality. This requires proper calibration and equipment maintenance when data is collected and when the prescription maps is used for variable rate application.

Problem Given that the 1, 2, and 4 ton/acre management zones areas were calculated to contain 450, 300, and 100 acres, respectively. What amount of lime would need to be purchased for an application following the prescription map in Fig. 29.9? How would this amount vary if a composite soil test recommendation was 2.25 ton/acre?

Solution Since the variable rate applicator will apply only the rate prescribed for each zone, the total amount required should be equal to the amount required in each management zone on the prescription map:

$$\text{Zone}_{1\text{ton/acre}} = 450 \text{ acres} \times \frac{1 \text{ ton}}{\text{acre}} = 450 \text{ tons}$$
$$\text{Zone}_{2\text{ton/acre}} = 300 \text{ acres} \times \frac{2 \text{ ton}}{\text{acre}} = 600 \text{ tons}$$
$$\text{Zone}_{4\text{ton/acre}} = 100 \text{ acres} \times \frac{4 \text{ ton}}{\text{acre}} = 400 \text{ tons}$$
$$\text{Total Lime} = 450 + 600 + 400 = 1450 \text{ tons}$$

The rate recommendation based on the single composite sample for the whole field is 2.25 ton/acre. First the overall number of acres is needed:

$$\text{Total Acreage} = 450 + 300 + 100 = 850 \text{ acres}$$
$$\text{Total Lime} = 850 \text{ acres} \times \frac{2.25 \text{ ton}}{\text{acre}}$$
$$\text{Total Lime} = 1912.5 \text{ or } 1910 \text{ tons}$$

In this problem, variable rate lime application required over 460 tons less than the single rate application. When using a standard composite soil test of the field, the resulting recommendation is highly dependent on how well the individual soil samples were chosen that when combined represent the overall average pH. In an ideal scenario, the variable rate prescription and the single rate recommendation would result in very similar amounts of lime applied. The real advantage of variable rate liming is the ability to manage the field at a much smaller scale to better adjust those areas that are much further from the average for the whole field (e.g., high and low pH areas).

29.7 Metric Problems

Problem What would be the calculated yield at the point in time when the in-cab monitor on a combine with a 6.10 m header displays a flow of 1.62 kg/s while harvesting wheat traveling 6.0 km/h?

Solution Substituting the three given values into the harvest yield equation along with the width, forward harvest velocity, and mass flow rate of harvest:

$$Y_{\text{mf}} = \frac{3.27 \times 36}{6.10 \times 6.0}$$

$$Y_{\text{mf}} = 3.2163\ldots \text{ or } 3.2\ \text{T/ha}$$

Problem Soybeans were harvested at a moisture content of 17 %MWB. The yield monitor displays a 4.1 T/ha yield at harvest. What would this yield at the elevator?

Solution Using Appendix XVI the standard moisture content is 13 %MWB for soybeans. Substituting this into the adjusted yield equation for moisture differences:

$$Y_{\text{adj}} = 4.1 \times \frac{100 - 17}{100 - 13}$$

$$Y_{\text{adj}} = 3.91149\ldots \text{ or } 3.9\ \text{T/ha}$$

After drying the soybeans down to a standard 13 %MWB, there is a 0.2 T/ha difference in the yield.

Appendices

Appendix I: Conventional Unit Conversions

Unit	Abbrev.	Conversion values			
1 Acre	ac	43,560 ft^3	160 $rods^2$		
1 British thermal unit	BTU	778.104 ft-lb	3.93 E − 4 hp-h		
1 Bushel	bu	2150.42 in^3	1.24446 ft^3	32 dry qt	
1 Foot	ft	12 in	0.3333 yd	6.061E − 2 rod*	
1 Foot, cubic	ft^3	1728 in^3	29.9 qt, liquid	7.481 gal, liquid	0.04 yd^3
1 Bushel	Bu	2150.42 in^3	32 qt, dry	1.24446 ft^3	
1 Foot-pound	ft-lb	3.239 E − 4 BTU	5.051 E − 7 hp/h	3.766 E − 7 kW/h	
1 Foot per second	ft/sec	0.68182 mi/h	0.1667 ft/min		
1 Foot, square	ft^2	144 in^2	6.9 E − 3 yd^2	9.29 E − 2 M^2	
1 Gallon, liquid	gal	231 in^3	0.13368 ft^3	4 liquid qt	
1 Gallon, dry	Gal	268.8 in^3			
1 Horsepower	hp	550 ft-lb/sec	33,000 ft-lb/min		
1 Inch	in	8.333 E − 2 ft	2.3 E − 3 yd		
1 Kilowatt	kW	737.612 ft-lb/sec	1.34111 hp	0.94796 BTU/sec	
1 Kilowatt-hour	kWh	2,655,403 ft-lb	3412.66 BTU	1000 W/h	
1 Mile	mi	63,360 in	5280 ft	1760 yd	320 rods
1 Mile per hour	mi/h	1.46667 ft/sec	88.0 ft/min		
1 Pound per square foot	lb/ft^2	6.944 *E* − 3 lb/in^2			

(continued)

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Unit	Abbrev.	Conversion values			
1 Pound per cubic foot	lb/ft^3	5.787 E − 4 lb/in^3			
1 Quart, liquid	qt	57.75 in^3	2 pt	32 oz	3.342 E − 2ft^3
1 Ton	T	2000 lb			
1 Watt	W	0.73761 ft-lb/sec	9.48 E − 4 BTU/sec	1.341 E − 3 Hp	
1 Yard	yd	36.0 in	3.0 ft		
1 Yard, square	Yd^3	1296 in^2	9.0 ft^3		
1 Yard, cubic	Yd^3	46,656 in^3	27 ft^3		

*E − 4 is the same as $\times 10^{-4}$

Appendix II: Conventional to SI Conversions

Quantity	From	To	Multiply by
Acceleration			
Vehicle	(mile/h)/s	(km/h)/s	1.609344
General	ft/s^2	m/s^2	0.3048
Area			
General	in^2	m^2	0.00064516
	ft^2	m^2	0.09290304
Pipe	in^2	mm^2	645.16
	in^2	cm^2	6.4516
	ft^2	m^2	0.09290304
Field	acre	ha	0.40469
Area per time			
Field operations	acre/h	ha/h	0.4046873
Consumption	gal/h	L/h	3.785412
	lb/(hp-h)	g/(kW-h)	608.2774
Density (mass)			
General ag products	lb/yd^3	kg/m^3	0.5932763
	lb/ft^3	kg/m^3	16.01846
Liquid	lb/gal	kg/L	0.1198264
Efficiency, fuel			
Highway vehicles	mile/gal	km/L	0.4151437
Off highway	hp-h/gal	kW-h/L	0.1969931
Energy			
Heat	Btu	kJ	1.055056
Use	kWh	MJ	3.6
Flow, Volume			
Air	ft^3/s	m^3/s	0.02831685
	ft^3/s	m^3/min	

(continued)

Quantity	From	To	Multiply by
Liquid, general	gal/min	L/min	
	gal/sec	L/s	3.785412
Fuel	gal/h	L/h	3.785412
River, channel	ft^3/s	m^3/s	0.02831685
Force			
Pedal, lever, general	lbf	N	4.448222
Drawbar	lbf	kN	0.00448222
Length			
	mile	km	1.609344
	rod	m	5.029210
	yd	m	0.9144
	ft	m	0.3048
	in	cm	2.54
	in	mm	25.4
Mass, general	lb	kg	0.4535924
	oz	g	28.34952
	t	T	0.90719
Power			
Heating	Btu/min	W	17.58427
	Btu/h	W	0.2930711
Engine	Hp	kW	0.7456999
Pressure	lb/in^2	kPa	6.894757
	lb/ft^2	kPa	0.04788026
	inHg	kPa	3.37685
	inH_2O	kPa	0.24884
Temperature	°F	°C	$\frac{t_{°F} - 32}{1.8}$
Torque	lbf	n-m	1.355818
	lbin		0.112984
Velocity, linear	mile/h	km/h	1.609344
	ft/s	m/s	0.3048
	in/s	mm/s	25.4
Volume	yd^3	m^3	0.7645549
	ft^3	m^3	0.02831685
	bushel	L	35.23907
	in^3	L	0.01638706
	gal	L	3.78412
	gal	gal (imperial)	0.8327
	qt	L	0.9463529
	acre-ft	m^3	1233.489
	bushel	m^3	0.03523907
Volume/area	gal/acre	L/ha	9.353958

Appendix III: Estimating Combine Losses

Crop	Seeds/ft^2 = Bu/ac	Seeds/m^2 = 50 kg/ha
Alfalfa	303	2426
Barley	14	140
Beans-red kidney	1.4	11
Beans-white	4	32
Canola	115	1063
Corn	2	17
Flax	1800	15,444
Oats	11	165
Rice	30	320
Rye	22	189
Sorghum	21	180
Soybeans	4	32
Wheat	19	152

Appendix IV: Efficiency, Speed Estimated Live and Repair Factors of Common Agricultural Machines

	Field efficiency		Field speed				Estimated life	Repair factors	
Machine	Range (%)	Typical (%)	Range (mi/h)	Typical (mi/h)	Range (km/h)	Typical (km/h)	h	RF1	RF2
Tractors									
two-wheel drive and stationary							12,000	0.007	2.0
four-wheel drive and crawler							16,000	0.003	2.0
Tillage and planting									
Moldboard plow	70–90	85	3.0–6.0	4.5	5.0–10.0	7.0	2000	0.29	1.8
Heavy duty disk	70–90	85	3.5–6.0	4.5	5.5–10.0	7.0	2000	0.18	1.7
Tandem disk harrow	70–90	80	4.0–7.0	6.0	6.5–11.0	10.0	2000	0.18	1.7
(Coulter) Chisel plow	70–90	85	4.0–6.5	5.0	6.5–10.5	8.0	2000	0.28	1.4
Field cultivator	70–90	85	5.0–8.0	7.0	8.0–13.0	11.0	2000	0.27	1.4
Spring tooth harrow	70–90	85	5.0–8.0	7.0	8.0–13.0	11.0	2000	0.27	1.4
Roller packer	70–90	85	4.5–7.5	6.0	7.0–12.0	10.0	2000	0.16	1.3

(continued)

Machine	Field efficiency		Field speed				Estimated life	Repair factors	
	Range (%)	Typical (%)	Range (mi/h)	Typical (mi/h)	Range (km/h)	Typical (km/h)	h	RF1	RF2
Mulcher-packer	70–90	80	4.0–7.0	5.0	6.5–11.0	8.0	2000	0.16	1.3
Rotary hoe	70–85	80	8.0–14.0	12.0	13.0–22.5	19.0	2000	0.23	1.4
Row crop cultivator	70–90	80	3.0–7.0	5.0	5.0–11.0	8.0	2000	0.17	2.2
Rotary tiller	70–90	85	1.0–4.5	3.0	2.0–7.0	5.0	1500	0.36	2.0
Row crop planter	50–75	65	4.0–7.0	5.5	6.5–11.0	9.0	1500	0.32	2.1
Grain drill	55–80	70	4.0–7.0	5.0	6.5–11.0	8.0	1500	0.32	2.1
Harvesting									
Corn picker sheller	60–75	65	2.0–4.0	2.5	3.0–6.5	4.0	2000	0.14	2.3
Combine	60–75	65	2.0–5.0	3.0	3.0–6.5	5.0	2000	0.12	2.3
Combine[a]	65–80	70	2.0–5.0	3.0	3.0–6.5	5.0	3000	0.04	2.1
Mower	75–85	80	3.0–6.0	5.0	5.0–10.0	8.0	2000	0.46	1.7
Mower (rotary)	75–90	80	5.0–12.0	7.0	8.0–19.0	11.0	2000	0.44	2.0
Mower-conditioner	75–85	80	3.0–6.0	5.0	5.0–10.0	8.0	2500	0.18	1.6
Mower-conditioner (rotary)	75–90	80	5.0–12.0	7.0	8.0–19.0	11.0	2500	0.16	2.0
Windrower (SP)[a]	70–85	80	3.0–8.0	5.0	5.0–13.0	8.0	3000	0.06	2.0
Side delivery rake	70–90	80	4.0–8.0	6.0	6.5–13.0	10.0	2500	0.17	1.4
Rectangular baler	60–85	75	2.5–6.0	4.0	4.0–10.0	6.5	2000	0.23	1.8
Large rectangular baler	70–90	80	4.0–8.0	5.0	6.5–13.0	8.0	3000	0.10	1.8
Large round baler	55–75	65	3.0–8.0	5.0	5.0–13.0	8.0	1500	0.43	1.8
Forage harvester	60–85	70	1.5–5.0	3.0	2.5–8.0	5.0	2500	0.15	1.6
Forage harvester	60–85	70	1.5–6.0	3.5	2.5–10.0	5.5	4000	0.03	2.0
Sugar beet harvester	50–70	60	4.0–6.0	5.0	6.5–10.0	8.0	1500	0.59	1.3
Potato harvester	55–70	60	1.5–4.0	2.5	2.5–6.5	4.0	2500	0.19	1.4
Cotton picker (SP)	60–75	70	2.0–4.0	3.0	3.0–6.0	4.5	3000	0.11	1.8
Miscellaneous									
Fertilizer Spreader	60–80	70	5.0–10.0	7.0	8.0–16.0	11.0	1200	0.63	1.3
Boom-type sprayer	50–80	65	3.0–7.0	6.5	5.0–11.5	10.5	1500	0.41	1.3
Air-carrier sprayer	55–70	60	2.0–5.0	3.0	3.0–8.0	5.0	2000	0.20	1.6

(continued)

Machine	Field efficiency		Field speed				Estimated life	Repair factors	
	Range (%)	Typical (%)	Range (mi/h)	Typical (mi/h)	Range (km/h)	Typical (km/h)	h	RF1	RF2
Bean puller-windrower	70–90	80	4.0–7.0	5.0	6.5–11.5	8.0	2000	0.20	1.6
Beet topper/ stalk Chopper	70–90	80	4.0–7.0	5.0	6.5–11.5	8.0	1200	0.28	1.4
Forage blower							1500	0.22	1.8
Forage wagon							2000	0.16	1.6
Wagon							3000	0.19	1.3

[a]SP indicates self-propelled machine

Appendix V: Draft Parameters and an Expected Range in Drafts Estimated by the Model Parameters for Tillage and Seeding Implements[a]

Implement	Width (units)	SI units machine parameters			Width (units)	English units machine parameters			Soil parameters			Range ± %
		C_1	C_2	C_3		C_1	C_2	C_3	F_1	F_2	F_3	
Major tillage tools												
Moldboard plow	m	652	0.0	5.1	ft	113	0.0	2.3	1.0	0.70	0.45	40
Chisel plow												
Straight point	tools	91	5.4	0.0	tools	52	4.9	0.0	1.0	0.85	0.65	50
Shovel or sweep	tools	107	6.3	0.0	tools	61	5.8	0.0	1.0	0.85	0.65	50
Twisted shovel	tools	123	7.3	0.0	tools	70	6.7	0.0	1.0	0.85	0.65	50
Sweep plow												
Primary tillage	m	390	19.0	0.0	ft	68	5.2	0.0	1.0	0.85	0.65	45
Secondary tillage	m	273	13.3	0.0	ft	48	3.7	0.0	1.0	0.85	0.65	35
Disk harrow, tandem												
Primary tillage	m	3.9	16.0	0.0	ft	53	4.6	0.0	1.0	0.88	0.78	50
Secondary tillage	m	216	11.2	0.0	ft	37	3.2	0.0	1.0	0.88	0.78	30
Disk harrow, offset												
Primary tillage	m	364	18.8	0.0	ft	62	5.4	0.0	1.0	0.88	0.78	50
Secondary tillage	m	254	13.2	0.0	ft	44	3.8	0.0	1.0	0.88	0.78	30
Field cultivator												
Primary tillage	tools	46	2.8	0.0	tools	26	2.5	0.0	1.0	0.85	0.65	30
Secondary tillage	tools	32	1.9	0.0	tools	19	1.8	0.0	1.0	0.85	0.65	25

(continued)

Implement	Width (units)	SI units machine parameters			Width (units)	English units machine parameters			Soil parameters			Range ± %
		C_1	C_2	C_3		C_1	C_2	C_3	F_1	F_2	F_3	
Row crop cultivator												
S-tine	rows	140	7.0	0.0	rows	80	6.4	0.0	1.0	0.85	0.65	15
C-shank	rows	260	13.0	0.0	rows	248	19.9	0.0	1.0	0.85	0.65	20
No-till	rows	435	21.8	0.0	rows	248	19.9	0.0	1.0	0.85	0.65	20
Minor tillage tools												
Rotary hoe	m	600	0.0	0.0	ft	41	0.0	0.0	1.0	1.0	1.0	30
Coil-tine harrow	m	250	0.0	0.0	ft	17	0.0	0.0	1.0	1.0	1.0	20
Spring-tooth harrow	m	2000	0.0	0.0	ft	135	0.0	0.0	1.0	1.0	1.0	35
Land plane	m	8000	0.0	0.0	ft	550	0.0	0.0	1.0	1.0	1.0	45
Seeding implements												
Row crop planter												
Mounted	rows	500	0.0	0.0	rows	110	0.0	0.0	1.0	1.0	1.0	25
Drawn	rows	900	0.0	0.0	rows	200	0.0	0.0	1.0	1.0	1.0	25
Row crop planter, no-till												
Three coulters/row	rows	3400	0.0	0.0	rows	765	0.0	0.0	1.0	0.94	0.82	35
Grain drill w/press wheels												
< 8 ft	rows	400	0.0	0.0	rows	90	0.0	0.0	1.0	1.0	1.0	25
8–12 ft	rows	300	0.0	0.0	rows	67	0.0	0.0	1.0	1.0	1.0	25
> 12 ft	rows	200	0.0	0.0	rows	25	0.0	1.0	1.0	1.0	1.0	25
Grain drill, no-till	rows	720	0.0	0.0	rows	160	0.0	0.0	1.0	0.92	0.79	35
Hoe drill												
Primary tillage	m	6100	0.0	0.0	ft	420	0.0	0.0	1.0	1.0	1.0	50
Secondary tillage	m	2900	0.0	0.0	ft	200	0.0	0.0	1.0	1.0	1.0	50
Pneumatic drill	m	3700	0.0	0.0	ft	250	0.0	0.0	1.0	1.0	1.0	50

[a]ASABE Standards 1997. Information for additional machines are included in the standards

Appendix VI: Solid Animal Waste Production and Characteristics

	Size		Production			Density		Nutrient content					
								Nitrogen		Potassium		Phosphorus	
Animal	(lb)	(kg[a])	(lb/day)	(kg/day)	Water (% WB)	(lb/ft^3)	(kg/m^3)	(lb/day)	(kg/day)	(lb/day)	(kg/day)	(lb/day)	(kg/day)
Dairy cattle	150	68	12.0	5.4	87.3	62.0	993	0.06	0.0272	0.010	0.0045	0.04	0.0181
	250	113	20.0	9.1	87.3	62.0	993	0.10	0.0454	0.020	0.0091	0.07	0.0318
	500	227	41.0	18	87.3	62.0	993	0.20	0.0907	0.036	0.0163	0.14	0.0635
	1000	454	82.0	37	87.3	62.0	993	0.14	0.0635	0.073	0.0331	0.27	0.1225
	1400	635	115.0	52	87.3	62.0	993	0.57	0.2586	0.102	0.0463	0.38	0.1724
Beef cattle	500	227	30.0	14	88.4	60.0	961	0.17	0.0771	0.056	0.0254	0.12	0.0544
	750	340	45.0	20	88.4	60.0	961	0.26	0.1179	0.084	0.0381	0.19	0.0862
	1000	454	60.0	27	88.4	60.0	961	0.34	0.1542	0.110	0.0499	0.24	0.1089
	1250	567	75.0	34	88.4	60.0	961	0.43	0.1950	0.140	0.0635	0.31	0.1406
Nursery pig	35	16	2.3	1.0	90.8	60.0	961	0.016	0.0073	0.0052	0.0024	0.010	0.0045
Growing pig	65	29	4.2	1.9	90.8	60.0	961	0.029	0.0132	0.0098	0.0044	0.020	0.0091
Finishing pig	150	68	9.8	4.4	90.8	60.0	961	0.068	0.0308	0.022	0.0100	0.045	0.0204
	200	91	13.0	5.9	90.8	60.0	961	0.090	0.0408	0.030	0.0136	0.059	0.0268
Gestating sow	275	125	8.9	4.0	90.8	60.0	961	0.062	0.0281	0.021	0.0095	0.040	0.0181
Sow and litter	375	170	33.0	15	90.8	60.0	961	0.23	0.1043	0.076	0.0345	0.15	0.0680
Boar	350	159	11.0	5.0	90.8	60.0	961	0.078	0.0354	0.026	0.0118	0.051	0.0231
Sheep	100	45	4.0	1.8	75.0	65.0	1041	0.045	0.0204	0.0066	0.003	0.032	0.0145
Layers	4	1.8	0.21	0.10	74.8	60.0	961	0.0029	0.0013	0.0011	0.0005	0.0012	0.0005
Broilers	2	0.9	0.14	0.06	74.8	60.0	961	0.0024	0.0011	0.00054	0.0002	0.00075	0.0003
Horse	1000	454	45.0	20	79.5	60.0	961	0.27	0.1225	0.0460	0.0209	0.1700	0.0771

[a]Direct conversion using 1 lb = 0.453924 kg

Appendix VII: Nutrient Utilization by Crops[a]

Crop	Yield		N		P_2O_5		K_2O	
			lb/ac	kg/ha	lb/ac	kg/ha	lb/ac	kg/ha
Corn	150 bu/ac	3.82 Mg/ha	185	207	80	90	215	241
	180 bu/ac	4.58 Mg/ha	240	269	100	112	240	269
Corn silage	32 tons	72 t/ha	200	224	80	90	245	274
Soybeans	50 bu/ac	1.36 Mg/ha	257	288	48	54	120	134
	60 bu/ac	1.64 Mg/ha	336	376	65	73	145	162
Grain sorghum	8000 lb/ac	3.64 Mg/ha	250	280	90	100	200	224
Wheat	60 bu/ac	1.36 Mg/ha	125	140	50	56	110	123
	80 bu/ac	2.18 Mg/ha	186	208	54	60	162	181
Oats	100 bu/ac	1.45 Mg/ha	150	168	55	62	150	168
Barley	100 bu/ac	2.18 Mg/ha	150	168	55	62	150	168
Alfalfa	8 tons	18 t/ha	450	504	80	90	480	538
Orchard grass	6 tons	13 t/ha	300	336	100	112	375	420
Brome grass	5 tons	11 t/ha	166	186	66	74	254	284
Tall fescue	3.5 tons	8 t/ha	125	140	65	73	185	207
Bluegrass	3 tons	7 t/ha	200	224	55	62	180	202

Source: Imperial values reproduced with permission from: *Structures and Environment Handbook*, MWPS-1, 11th edition, revised 1987, Midwest Plan Service, Ames, IA 50011–3080
[a]SI values are direct conversions rounded to the nearest whole unit

Appendix VIII: Maximum Annual Application Rates for Phosphates Based on Soil Family

Soil families	% Clay	PH			
		6.0–7.5		<6.0 or >7.5	
Sandy	<10	300	336 kg/ha	300 lb/ac	336 kg/ha
Coarse-loamy and coarse-silty	11–18	400 lb/ac	448 kg/ha	500 lb/ac	560 kg/ha
Fine-loamy and fine-silty	19–35	450 lb/ac	504 kg/ha	600 lb/ac	672 kg/ha
Fine	36–60	500 lb/ac	560 kg/ha	750 lb/ac	840 kg/ha
Very fine	>60	500 lb/ac	560 kg/ha	750 lb/ac	840 kg/ha
Loamy-skeletal	15–35	150 lb/ac	168 kg/ha	200 lb/ac	224 kg/ha
Clayey-skeletal	>35	250 lb/ac	280 kg/ha	350 lb/ac	392 kg/ha

Appendix IX: Insulating Properties of Various Building Materials[a]

Description	Thickness	Density (lb/ft^3)	Resistance (per inch)[b] $\left(\frac{°Fft^2h}{Btu\ in}\right)$	Description
Building board				
Asbestos cement		120	0.25	
Gypsum or plaster	0.375 in	50		0.32
	0.5 in	50		0.45
Plywood (Douglas fir)	0.625 in	50 34	1.25	0.56
Vegetable fiber board				
Sheathing, regular density	0.5 in	18		1.32
Sheathing, intermediate density	0.5 in	22		1.09
Sound-deadening board	0.5 in	15		1.35
Laminated paperboard		30	2.00	
Hardboard				
Medium density		50	1.37	
High density		55	1.22	
Particleboard				
Low density		37	1.41	
Medium density		50	1.06	
High density		62	1.18	
Underlayment	0.625 in	40	1.22	
Waferboard		37	1.59	
Wood subfloor	0.75 in			0.94
Building membrane				
Vapor-permeable felt				0.06
Vapor-seal, 2 layers of mopped 15-lb. felt				0.12
Finish flooring materials				
Carpet and fibrous pad				2.08
Carpet and rubber pad				1.23
Cork tile	0.125 in			0.28
Terrazzo	1 in			0.08
Tile-asphalt, linoleum, vinyl, rubber				0.05
Insulating materials				
Blanket or batt, mineral fiber processed from rock, slag, or glass				
	3–4 in	0.4–2.0		11.0
	3.5 in	0.4–2.0		13.0
	3.5 in	1.2–1.6		15.0

(continued)

Description	Thickness	Density (lb/ft^3)	Resistance (per inch)[b] $\left(\frac{^\circ Fft^2h}{Btu\ in}\right)$	Description
	5.5–6.5 in	0.4–2.0		19.0
Boards and slabs				
Cellular glass		8.0		
Glass fiber		4.0–9.0	4.0	
Expanded perlite		1.0	2.78	
Expanded rubber		4.5	4.55	
Expanded polystyrene, extruded, smooth		1.8–3.5 in	5.00	
Expanded polystyrene, molded beads		1.0	3.85	
		1.25	4.00	
		1.5	4.17	
		1.75	4.17	
Cellular polyurethane/ polyisocyanurate		1.5	6.25–5.56	
Cellular phenolic, closed cell		3.0	8.20	
Mineral fiberboard				
Core or roof insulation		16–17	2.94	
Acoustical tile		18.0	2.86	
		21.0	2.70	
Cement fiber slabs				
Wood and Portland cement binder		25.0–27.0	2.0–1.89	
Wood and magnesia oxysulfide binder		22.0	1.75	
Lose fill				
Cellulosic		2.3–3.2	3.7–3.13	
Perlite, expanded		2.0–4.1	3.7–3.3	
		4.1–7.4	3.3–2.8	
		7.4–11.0	2.8–2.4	
Mineral fiber (rock, slag, or glass)				
	3.75–5 in	0.6–2.0		11.0
	6.5–8.75 in	0.6–2.0		19.0
	7.5–10.0 in	0.6–2.0		22.0
Vermiculite, exfoliated		7.0–8.2	2.13	
		4.0–6.0	2.27	
Spray applied				
Polyurethane foam		1.5–2.5	6.25–5.56	
Urea-formaldehyde		0.7–1.6	4.53–3.57	
Cellulosic fiber		3.5–6.0	3.45–2.94	
Glass fiber		3.5–4.5	3.85–3.70	

(continued)

Description	Thickness	Density (lb/ft^3)	Resistance (per inch)[b] $\left(\frac{°Fft^2h}{Btu\ in}\right)$	Description
Roofing				
Asbestos-cement shingles		120		0.21
Asphalt roll roofing		70		0.15
Asphalt shingles		70		0.44
Slate	0.5 in			0.05
Wood shingles				0.94
Plastering materials				
Cement plaster sand aggregate		116	0.20	
Gypsum plaster				
Lightweight aggregate	0.5 in	45		0.32
Lightweight aggregate	0.625 in	45		0.39
Masonry materials				
Brick, fired clay		150	0.12–0.10	
		130	0.16–0.12	
		120	0.18–0.15	
		100	0.24–0.20	
		80	0.33–0.27	
Clay tile, hollow				
1 cell deep	3 in			0.80
	4 in			1.11
2 cells	6 in			1.52
	10 in			2.22
3 cells	12 in			2.50
Concrete blocks				
Normal weight aggregate				
8 in. 33–36 lb				1.11–0.97
With perlite-filled cores				2.0
With vermiculite cores				1.92–1.37
12 in. 50 lb, 2 cores				1.23
Lightweight aggregate				
6 in. 16–17 lb				1.93–1.65
With perlite-filled cores				4.2
With vermiculite cores				3.0
8 in. 19–22 lb				3.2–1.90
With perlite-filled cores				6.8–4.4
With vermiculite cores				5.3–3.9
12 in. 32–36 lb				2.6–2.3
With perlite-filled cores				9.2–6.3
With vermiculite cores				5.8
Stone, lime, or sand		180	0.01	
		160	0.02	
		140	0.04	
		120	0.08	

(continued)

Description	Thickness	Density (lb/ft^3)	Resistance (per inch)[b] $\left(\frac{^\circ F ft^2 h}{Btu\ in}\right)$	Description
Marble and granite		180	0.03	
		160	0.05	
		140	0.06	
		120	0.09	
		100	0.13	
Woods				
Hardwoods				
Oak		41.2–46.8	0.89–0.80	
Birch		42.6–45.4	0.87–0.82	
Maple		39.8–44.0	0.92–0.84	
Ash		38.4–41.9	0.94–0.88	
Softwoods				
Southern pine		35.6–41.2	1.00–0.89	
Douglas Fir-Larch		33.5–36.3	1.06–0.99	
Southern cypress		31.4–32.1	1.11–1.09	
West Coast cedar		21.7–31.4	1.48–1.11	
California redwood		24.5–28.0	1.35–1.22	
Windows[b]				
Single glazed				0.06
With storm windows				1.15
Insulating glass, 1/4 air space				
Double pane				0.84
Triple pane				1.71
Air space, 3/4–4 inches				0.90
Surface conditions				
Inside surface				0.68
Outside surface				0.17
Floor				
Concrete slab on ground				1.23
Concrete slab with insulation				2.22

[a]Reprinted from Introduction to Agricultural Engineering, 2nd edition

[b]For conversion to SI units $R_{SI} = 5.678\ R_{Cust}$. R_{SI} is in units of $\frac{^\circ C\ m^2\ h}{kJ}$. R_{Cust} is in units of $\frac{^\circ F\ ft^2\ h}{BTU}$.

Appendix X: Moisture and Heat Produced[a]

Animal	Moisture[b] (lb water/h)	Heat[a] (BTU/h)
Swine		
10–50 lb	0.065	174.0
50–100	0.177	240.0
100–200 lb	0.219	354.0
Broiler		
0.22–1.5 lb	0.0079	12.4
1.5–3.5 lb	0.0110	18.7
Turkey		
1 lb	0.0059	10.8
2 lb	0.0025	9.8
Dairy cow	1.196	1917.0
Equipment		
Incandescent lighting		3.4 Btu/h-watt
Fluorescent lighting		4.1 Btu/h-watt
Electric motors		4000 Btu/h-Hp

[a]Reproduced with permission from: *Structures and Environment Handbook*, MWPS-1, 11th edition, revised 1987, Midwest Plan Service, Ames, IA 50011–3080
[b]The amount of water and heat released by animals changes as the air temperature changes. These are average values

Appendix XI: Allowable Fiber Stress by Species

Use	Grade	Size		Allowable fiber stress[a] (lb/in^2)
		Thick	Wide	
Douglas fir and Larch (19% moisture)				
Structural light framing				
	Select structural	2–4″	2–4″	1200
	No. 1			1050
	No. 2			850
Light framing	Construction	2–4″	4″	625
	Standard			350
	Utility			175
Southern pine (19% moisture)				
Structural light framing				
	Select structural	2–4″	2–4″	1150
	No. 1			1000
	No. 2			825
	Stud			450

(continued)

Use	Grade	Size		Allowable fiber stress[a] (lb/in^2)
		Thick	Wide	
Light framing	Construction	2–4″	4″	600
	Standard			350
	Utility			150

Source: Reproduced with permission from: *Structures and Environment Handbook*, MWPS-1, 11th edition, revised 1987, Midwest Plan Service, Ames, IA 50011–3080
[a]For lumber milled and used at 15% moisture, multiply by 1.08 for allowable fiber stress

Appendix XII: Copper Resistance (Ohms/1000 ft)

Wire size (AWG)	Resistance (Ohms/1000 ft)
22	16.46
20	10.38
18	6.51
16	4.09
14	2.58
12	1.62
10	1.02
8	0.64
6	0.41
4	0.26
2	0.16
0	0.10

Appendix XIII: Copper Resistance (Ohms/100 m)

Wire size (mm^2)	Resistance (Ohms/100 m)
1.5	1.073
2.5	0.676
4.0	0.423

Appendix XIV: Copper Wire Sizes for 120 Volt, Single Phase, 2% Voltage Drop

Minimum allowable size				Run of wire (ft)													
	In cable, conduit, and earth			Compare size shown below with size shown under minimum allowable size and the used the larger size													
Load (amp)	R,T, TW	RH, RHW, THW	Overhead in air, bare and covered conductor	50	75	100	125	150	175	200	225	275	300	350	400	450	500
5	14	14	10	14	14	12	12	10	10	10	8	8	8	6	6	6	6
7	14	14	10	14	12	12	10	10	8	8	8	6	6	6	6	4	4
10	14	14	10	12	12	10	8	8	8	6	6	6	4	4	4	4	3
15	14	14	10	12	10	8	6	6	6	6	4	4	4	3	2	2	2
20	14	12	10	10	8	6	6	6	6	4	4	3	3	2	1	1	0

Appendix XV: Copper Wire Sizes for 120 Volt, Single Phase, 2% Voltage Drop

Minimum allowable size				Run of wire (ft)													
	In cable, conduit, and earth			Compare size shown below with size shown under minimum allowable size and the used the larger size													
Load (amp)	R,T, TW	RH, RHW, THW	Overhead in air, bare and covered conductor	50	75	100	125	150	175	200	225	275	300	350	400	450	500
5	14	14	10	14	14	14	14	14	12	12	12	12	10	10	8	8	6
7	14	14	10	14	14	14	14	12	12	12	10	10	10	8	8	6	6
10	14	14	10	14	14	12		2	10	10	10	10	8	6	6	6	4
15	14	14	10	14	12	12	10	10	8	8	8	8	6	4	4	4	2
20	12	12	10	12	12	10	8	8	8	6	6	6	4	4	2	2	2

Appendix XVI: Standard Test Weight and Marketable Moisture Content

Crop (seed)	Test weight (lb/bu)	Moisture content (%MWB)
Barley	48	14.5
Corn	56	15.5
Grain sorghum	57	14.0
Oats	32	14.0
Soybean	60	13.0
Wheat	60	13.5

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